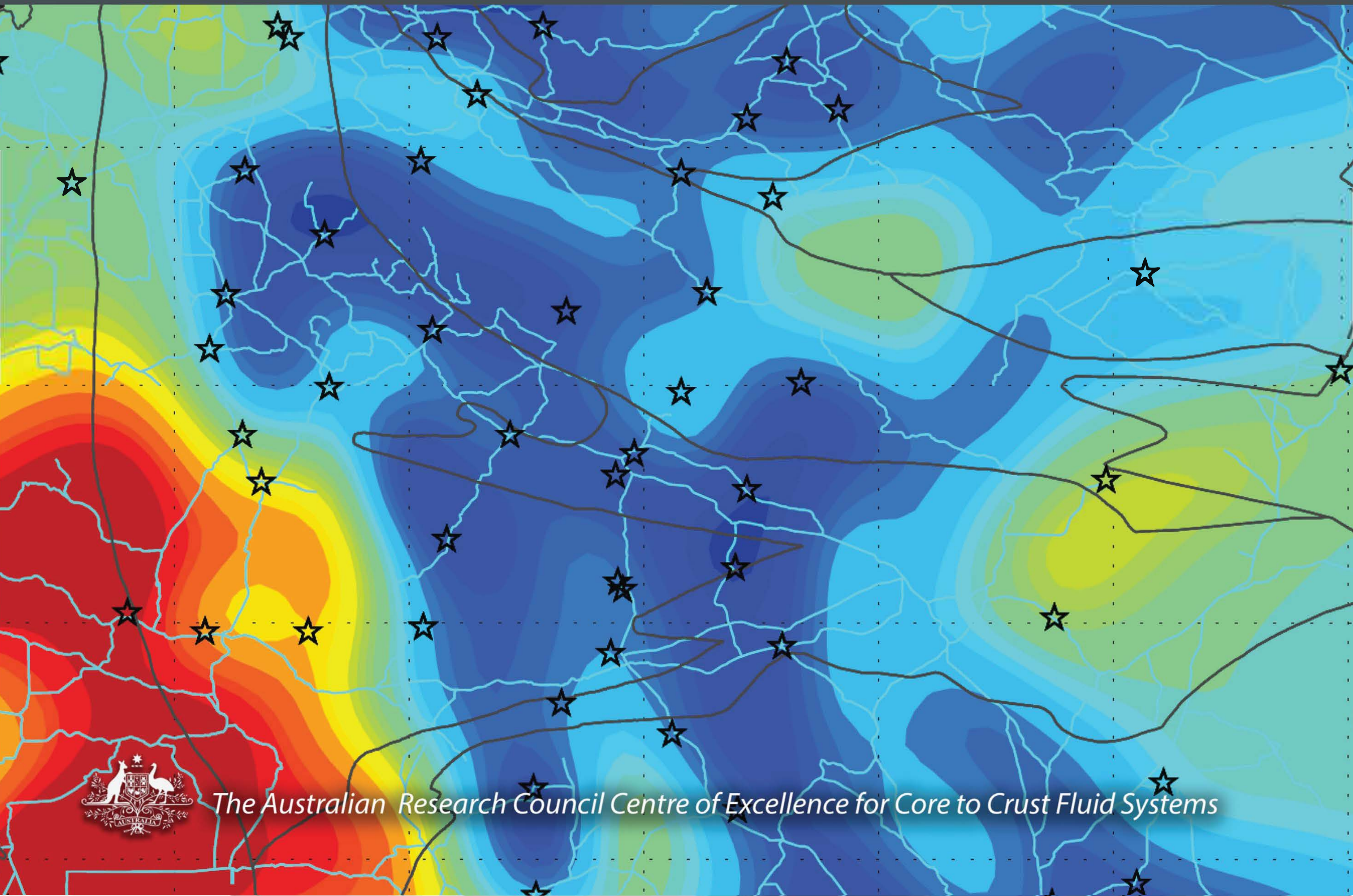
CCFS

2015 Annual Report



The Australian Research Council Centre of Excellence for Core to Crust Fluid Systems

- CCFS information is accessible on WWW at:

  http://www.ccfs.mq.edu.au/

- Contact CCFS via email at:

  ccfs.admin@mq.edu.au

The CCFS Annual Report is available from our website http://www.ccfs.mq.edu.au/ as a downloadable pdf file or in html format, and by mail on USB on request.

Front Cover: A contrast of scale from micro (top: Cathodoliminescence of a corundum crystal, Research highlight pp. 70-71) to macro (bottom: Shear wave velocity map from the COPA deployment, Capricorn Origen, WA, Research highlight pp. 34-36). Cover by Sally-Ann Hodgekiss.

Contents

Australian Government
Australian Research Council

Established and supported under the Australian Research Council's Research Centres Program

Director's preface

This report summarises the activities and achievements of the Australian Research Council Centre of Excellence for Core to Crust Fluid Systems (CCFS) in 2015 (commenced mid 2011). Activities include research, technology development, stakeholder engagement, international links and research training.

The overarching goal of CCFS is to understand Earth's internal dynamics, evolution and fluid cycles from core to crust. CCFS multiplies the capabilities of three national centres of research excellence in Earth and Planetary Sciences: Macquarie University (Administering Institution), Curtin University and the University of Western Australia (Collaborating Institutions). The Geological Survey of Western Australia is a Partner Institution and researchers from Monash University and the University of New South Wales are formally affiliated. Our strong formal international partnerships and growing networks leverage our resources across intellectual, infrastructure and funding bases.

2015 saw the implementation of seven Flagship Programs following the extensive review and program restructuring carried out in 2014 based on the benchmark outcomes of the first 3 years and extending in new directions, or finalisation of programs that had come to fruition. The Flagship Programs are targeting the research goals through to 2018 with a new focus and realigning strategies to deliver further transformational outcomes and leave a legacy in knowledge, new technology and methodologies. They are providing vital new knowledge about Australia's geological evolution to guide smart new mineral exploration and to fulfil the CCFS vision of ***"Delivering the fundamental science needed to sustain Australia's resource base"***. These Flagship Programs are underpinned by two Technology Development Programs, designed to deliver more leading-edge geochemical breakthroughs, capitalising on the outstanding geochemical instrumental infrastructure across CCFS.

New instrumentation installed and operational in 2015 includes the Cameca LEAP 4000X HR atom probe coupled with a Tescan LYRA Focused ion beam scanning electron microscope with time-of-flight secondary ion mass spectrometry capability at Curtin University, a Cameca 50L NanoSIMs at the University of Western Australia and the Nu Plasma II inductively-coupled-plasma mass spectrometer in the Geochemical Analysis Unit at Macquarie. The *in situ* measurement of U-Pb isotopes in zircon using the combination of the femtosecond laser system and Nu Plasma II is a world first, providing greater sensitivity and better spatial resolution; and preliminary results were reported at the Goldschmidt Conference in Prague, 2015 (see *Appendix 6*).

The outstanding quality of CCFS researchers, and their continuing success in gaining external leverage of resources, are exemplified by the award of more prestigious Fellowships in 2015. Zheng-Xiang Li was awarded an ARC Laureate Fellowship; Olivier Alard and Kate Selway received ARC Future Fellowships to commence in 2016 (see *pp. 11-12*) – a total of eleven Future Fellowships awarded to researchers in CCFS; and Andrea Giuliani embarked on his ARC DECRA Fellowship.

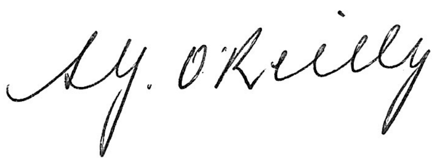
Highlights of prestigious external awards for CCFS Chief investigators included the 2016 Australian Academy of Science (AAS) Nancy Millis Medal to Elena Belousova, the presentation of the AAS Anton Hales Medal Lecture by Yingjie Yang, and the presentation of the Royal Society of NSW W.B. Clarke Memorial Lecture by Bill Griffin. Four CCFS Chief investigators (Bill Griffin, Sue O'Reilly, Zheng-Xiang Li and Simon Wilde) were honoured at the 2015 Thomson Reuters Citation & Innovation Awards for their Contribution to the Understanding of the "*Tectonic Setting of the North and South China Cratons*".

The lively postgraduate cohort kept growing with 76 PhD students undertaking research aligned with CCFS. CCFS postgraduates are producing world-class research with authorship of 28 publications in high-impact journals in 2015 and 59 presentations at peak international workshops and conferences.

Leading-edge research outcomes in 2015 include a wide spectrum of discoveries, including: stunning new images of the deep crustal structure of the western half of the Australian continent; the discovery of 3-billion year old crust hidden beneath the Ukrainian Shield (an analogue for western Australia's deep crust?); opening a window to the deep structure beneath western Victoria; the first analysis of deformation styles in the mantle transition zone (>400 km beneath the Earth's surface); enigmatic minerals from Earth's mantle, previously only recorded in meteorites; new ore-forming deep crustal processes; the world-first *in situ* characterisation of lithium isotope behaviour in zircon. These are all included in the "*Research highlights*" section (*pp. 33-75*).

The world-leading outcomes on the structure and composition of the deep Earth, the behaviour of its materials, and the nature and mechanisms of fluid processes from >400 km depth to the surface, all improve our knowledge directly, or by analogy, of the hidden deep geology beneath Australia. The new outcomes and the novel methodologies (geophysical and geochemical), are rewriting the canon of Australia's evolution to the continent we know today. CCFS has become acknowledged as a key resource for providing the fundamental research to underpin the national UNCOVER initiative (http://www.uncoverminerals.org.au/).

The ultimate goal is to continue to lead the way to Australia's future mineral security, ensuring economic health for our society through fundamental, high-impact research discoveries.



Professor S.Y. O'Reilly

CCFS participants at the annual Research Meeting held on 22-23 October 2015.

The Australian Research Council Centre of Excellence for Core to Crust Fluid Systems (CCFS): Background

Vision

Delivering the fundamental science needed to sustain Australia's resource base

GOALS - THE MISSION

- **to reach a new level of understanding of Earth's internal dynamics and fluid cycles, and how these have evolved to generate the hydrosphere, continents and atmosphere**
- **to provide a world-leading interdisciplinary research environment for the development of the next generation of Australia's geoscientists**
- **to deliver new concepts about the spatial and temporal distribution of Earth resources to the minerals and energy industries**
- **to develop new educational approaches that can renew and revitalise Australian research in the Earth Sciences**

CONTEXT

Water is essential for human existence, indeed for life's beginning. The circulation of water and other fluids lubricates the deep-seated dynamics that keep Earth geologically alive, and its surface habitable. Several oceans worth of water may be present inside Earth, and the exchange of water and other fluids between the surface and the deep interior plays a crucial role in most Earth systems, including the evolution of the surface, the hydrosphere, the atmosphere, the biosphere, and the development of giant ore deposits.

Subduction - the descent of oceanic plates into the mantle - carries water down into Earth's interior; dehydration of the subducting crustal slabs at high pressure and temperature releases these fluids into the mantle, causing melting and controlling the strength, viscosity, melting temperature and density of rocks in the deep Earth, as well as the structure of major seismic discontinuities at 410 and 660 km depth. The partial return of some of these materials to the surface through mantle-plume activity provides a mechanism for tectonic cyclicity, which may have varied over geological time. These effects dominate solid-Earth dynamics and make plate tectonics possible, but the origin, abundance, speciation and movements of fluids in the deep interior are largely unknown, and represent key issues in modern geoscience.

Until recently, a real understanding of the workings of Earth's deep plumbing system has been tantalisingly out of our reach. Now, rapid advances in geophysics are producing stunning new images of variations in physical properties such as seismic velocity and electrical conductivity in the deep Earth, but interpretation of these images in terms of processes and Earth's evolution is only in its developmental stages. It requires new kinds of data on deep-Earth materials, and especially on the effects of deep fluids and their circulation.

To provide the knowledge needed to reach a new level of understanding of Earth's evolution, dynamics and fluid cycle(s) through time, CCFS will integrate information across geology, tectonics, experimental and analytical geochemistry, petrophysics, geophysics, and petrophysical and dynamical modelling. These disciplines have traditionally represented '*research silos*', but we will bring them together to provide a significant increase in our national research capability.

2015 CENTRE RESEARCH MEETING

A successful and productive CCFS Research Meeting was held on 22-23 October 2015. The meeting provided the opportunity for participants, as well as members of the CCFS Board, to hear research presentations from CCFS researchers, including postgraduates and ECRs.

The forum was a catalyst for new, exciting ideas and cemented collaboration among researchers of the Centre's nodes and partner institutions.

The meeting also provided an opportune time for a CCFS Board Meeting.

Top-Bottom, L-R; Cam McCuaig, Bob Loucks, Jun Xie, Xiong Lu, Siqi Zheng, Sue O'Reilly, Sandra Piazolo, Laure Martin, Vikraman Selvaraja, Chris Grose, Andrea Giuliani, Beñat Oliveira Bravo, Chengxin Xiang, Ian Tyler, Heta Lampinen, Christopher Gonzalez, Galen Halverson and Marco Fiorentini.

CCFS Advisory Board Meeting, 21 October, 2015.

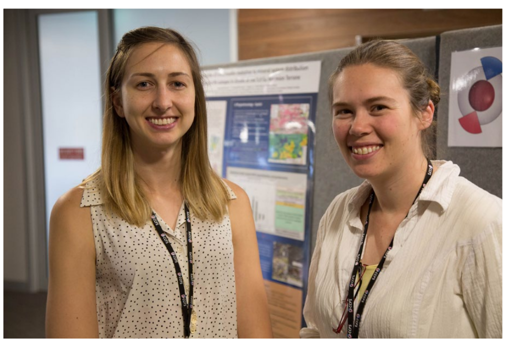


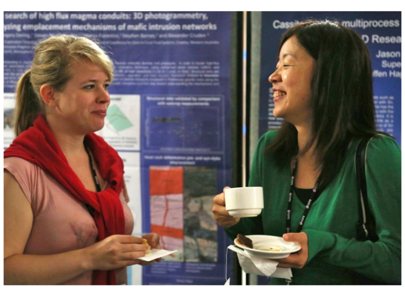
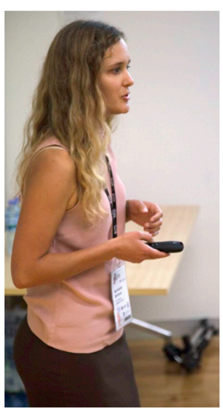










Top-Bottom, L-R; Weronika Gorczyk, Norman Pearson, Martin Van Kranendonk, David Adams, Sarah Gain, Irina Tretiakova, Zhen Guo, Chengxin Jiang, Huaiyu Yuan, Kai Wang, Beñat Oliveira Bravo, Nicole McGowan, Rosanna Murphy, Erica Barlow, Victoria Elliot, Steve Craven, Nora Liptai, Takako Satsukawa, Katerina Bjorkman, Sam Mathews and Jonathon Wasiliev.

CENTRE RESEARCH

Research programs within the Centre are focused to provide maximum synergy for the scope enabled by the resource base. As it is not possible to encompass the full range of research about the Earth's fluid cycle and deep Earth dynamics, all applied and mature strategic research is carried out in parallel, supported by other funding sources. The Research Program structure was revised in 2014 to ensure the overarching goals were being fulfilled. The resulting Flagship Programs (see *p. 18*) were put in place as cross-node streams contributing to the three global Themes (Early Earth, Earth's Evolution and Earth Today).

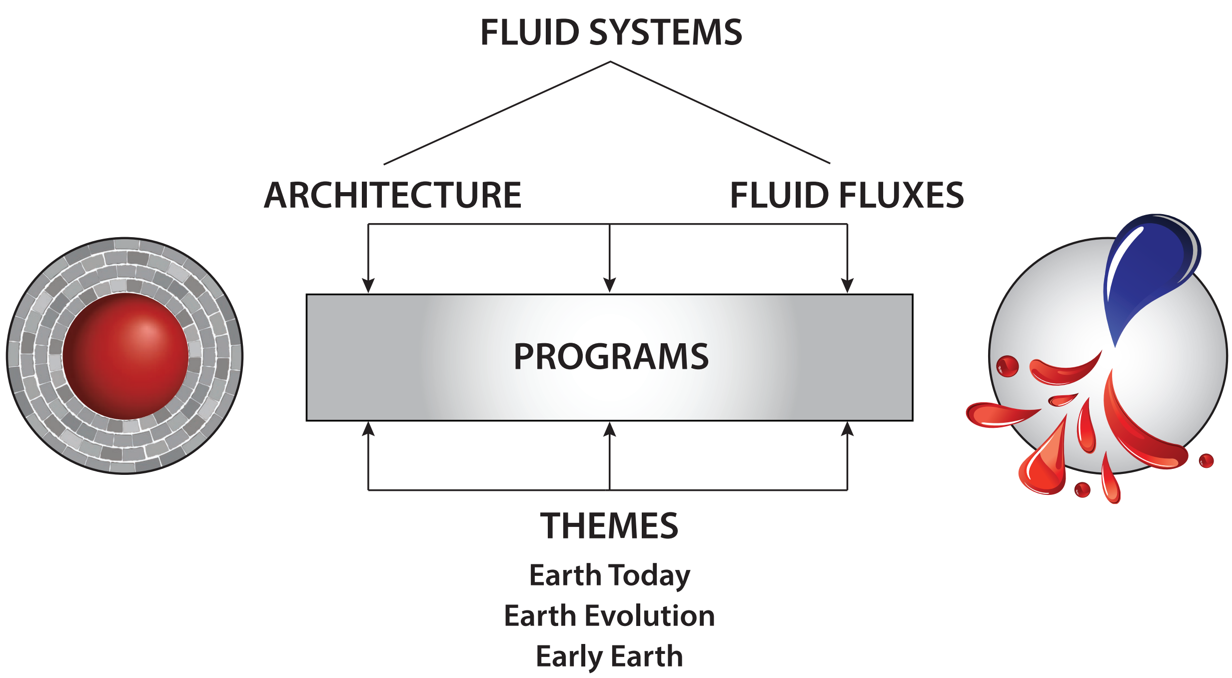
These are structured to capitalise on the people and resource context of the Centre in a way not possible with a shorter timeframe, or without the critical mass of research expertise, depth and breadth. More detailed information is given in *"The CCFS research program"* and *"Research highlights"*.

In order to track the input of coalescing strands, the concept of programs contributing to understanding ***Earth Architecture*** and/or ***Fluid Fluxes*** helps track the pieces of the giant 4-dimensional Earth puzzle being solved by CCFS and encapsulates the relationship of all the CCFS programs to Earth *'fluids'*.

"Architecture" is the 'roadmap' for fluids

"Fluid Fluxes" represents the 'traffic report'

All Research highlights and Programs are now keyed to this framework shown diagrammatically below:



Aerial view from above the Xigaze ophiolite complex outcropping near the Chongdui and Qunrang villages, southern Tibet (photo Zheng-Xiang Li).

THEMES

THEME 1: EARLY EARTH

The Early Earth - Its formation and fluid budget. This theme focuses on the nature of Earth's early differentiation and the role of fluids. Ancient (>3 Ga) rocks may yield evidence for early life, and analysing the mass-independent fractionation of Fe and S isotopes will allow us to test the involvement of biological processes in ancient deposits.

The earliest record of Earth's magnetic field will provide new information on when the core's geodynamo formed and the geometry and intensity of its field, and will be used to track the movement of Archean tectonic plates. The geochemical nature and dynamic behaviour of the mantle in the early Earth will be assessed using *in situ* analysis of targeted minerals from a variety of mantle rock types and tectonic environments, coupled with dynamic modelling.

THEME 2: EARTH'S EVOLUTION

Earth's Evolution - Fluids in crustal and mantle tectonics; recycling of fluids into the deep mantle; hydrosphere, atmosphere and the deep Earth. Earth has evolved through cycles of crustal formation and destruction, punctuated by '*tipping points*', when rapid cascades of interlinked events produced dramatic changes in the composition of the oceans, the oxygen levels of the atmosphere, the tectonic behaviour of the crust and mantle, and the distribution of mineral and energy resources. These events changed the distribution and behaviour of fluids in the deep Earth, and each altered Earth's evolution irreversibly.

Key issues are: when did subduction start; how did it contribute to the Earth's cooling; how has this process evolved through time? Isotopic studies will define the rates of continental growth *vs* recycling through time, and test linkages between crust and mantle events. Geophysical imaging and dynamic modelling will be used to build 3D models of subduction dynamics, thermal evolution and geodynamic cycles. Stable-isotope studies will track water and other fluids in their cycles through the Earth and the hydrosphere.

THEME 3: EARTH TODAY

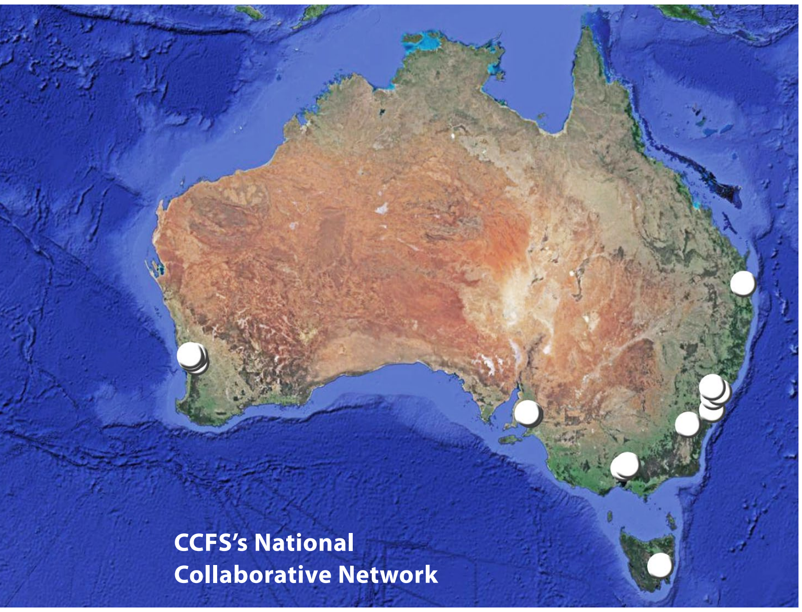
Earth Today - Dynamics, decoding geophysical imaging, and Earth resources. Geophysical imagery gives us a snapshot of the current status of the deep Earth but also carries the imprints of past processes. Realistic interpretation of these data will give us new insights into Earth's internal dynamics and will have practical consequences, e.g. for resource exploration. We will develop thermodynamically and physically self-consistent dynamic codes to model complex processes and their expression in geophysical and geochemical observables. These codes will be used to identify the processes that have controlled the fluid cycle through Earth's history.

Measurement of the physical properties of potential deep Earth materials at extreme conditions will feed into petrophysical modelling of seismic data in terms of composition, temperature and anisotropy. Measurements of metal complexing at realistic conditions that mimic real ore-system fluids/melts will provide new ways to interpret observations on fluid/melt inclusions in minerals. We will investigate the role of organo-metallic compounds in metal transport, using the capabilities of the Australian Synchrotron, to understand the role of such compounds in the formation of large mineral systems.

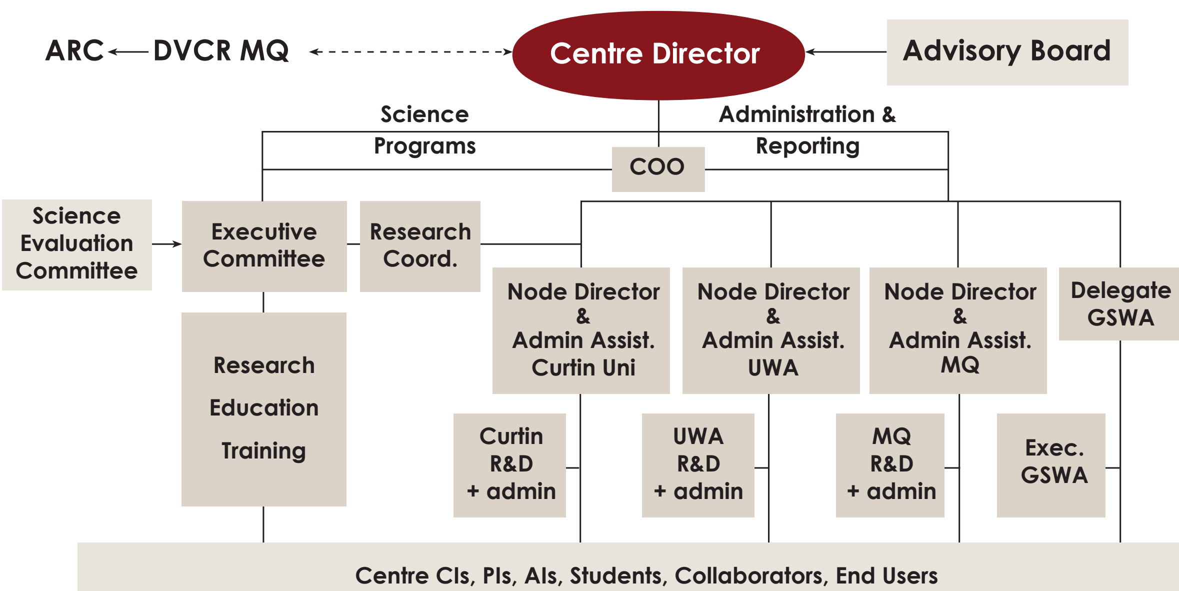
Wild camel racing along the Tangadee road on the way from the Abra Mining Ltd Pty exploration camp to Tangadee Station (photo Heta Lampinen).

Structure

CCFS builds on a world-class infrastructure base, and multiplies the capabilities of three internationally recognised centres of research excellence: Macquarie University (Administering Institution), Curtin University and the University of Western Australia. The Geological Survey of Western Australia is a Partner Institution and researchers from Melbourne University and the University of New South Wales are formally affiliated. The overseas nodes led by Partner Investigators in France, China, Germany and the USA are contributing resources and provide access to a wide variety of expertise and instrumental capabilities. Memoranda of Understanding (MOU) for research collaboration and postgraduate exchange and joint programs, provide formal affiliations with four additional global institutions with leading reputations in the field. CCFS also has formal Cotutelle MOU with a further 19 global institutions (see *p. 98*). CCFS incorporates several pre-existing centres within the Administering and Collaborating Institutions: the GEMOC Key Centre (http//www.gemoc.mq.edu.au/) at Macquarie University retains its structure and is fully incorporated within CCFS; the research and strategic activities of CET (Centre for Exploration Targeting; http://www.cet.edu.au/) at the University of Western Australia lie within CCFS; and the activities of TiGeR (http://tiger.curtin.edu.au/) at Curtin University are also aligned with CCFS.


CCFS's National Collaborative Network

There is active national collaboration with state Geological Surveys, Geoscience Australia (GA), CSIRO, the Australian National University (RSES), University of Newcastle, the University of Sydney, the University of Wollongong, the University of Adelaide and several major industry collaborators (national and global), across a broad range of programs related to the CCFS strategic goals. A distinctive feature of CCFS is the high level of active international collaborations and reciprocal links (see the section on *International links*).



Governance & management

Centre Director Professor Suzanne O'Reilly is supported by a Chief Operating Officer and a Reporting and Communications Manager. Professor O'Reilly provides scientific leadership and strategic direction for the Centre. Node Directors administer the CU and UWA nodes and are responsible for providing leadership in their respective nodes, bringing together researchers to form a coherent team with a shared vision of the whole CoE's aims and objectives. The Geological Survey of Western Australia has a nominated representative.

Professor O'Reilly chairs an Executive Committee which guides the Advisory Board and Centre Director on the appropriateness of the research strategies, reports on progress in achieving aims as well as structure and general operating principles, and identifies and protects the Centre IP. A new Executive position of Centre Research Coordinator was introduced in 2013, taken on by the targeted MQ appointment of Professor Stephen Foley.

The Advisory Board includes senior representatives from industry and other end users such as Geoscience Australia. This model has proven highly productive during the lifetimes of the GEMOC Key Centre and CET. The Board meets at least annually to provide advice on the research program and governance, and any other matters relevant to CCFS. The six external members of the Advisory Board are actively engaged and supportive of CCFS (95% attendance at meetings) and extensively workshopped the new vision statement to reflect the national benefit deriving from the fundamental research in CCFS.

The Science Advisory Committee has a rotating membership and primarily evaluates the Centre's research, in particular its research strategies, structure and outcomes.

Executive Committee

Professor Suzanne Y. O'Reilly - Director
Department of Earth and Planetary Sciences
Macquarie University

Professor William L. Griffin
Department of Earth and Planetary Sciences
Macquarie University

Associate Professor Craig O'Neill
Department of Earth and Planetary Sciences
Macquarie University

Professor Simon Wilde - Node Director
Department of Applied Geology
Curtin University

Professor Zheng-Xiang Li
Department of Applied Geology
Curtin University

Professor Campbell McCuaig - Node Director
School of Earth and Environment
University of Western Australia

Professor Marco Fiorentini
School of Earth and Environment
University of Western Australia

(Ex Officio)

Professor Stephen Foley - Research Coordinator
Department of Earth and Planetary Sciences
Macquarie University

Dr Ian Tyler - GSWA
Assistant Director Geoscience Mapping
Geological Survey of Western Australia

Magdalene Wong-Borgefjord - COO
Department of Earth and Planetary Sciences
Macquarie University

Advisory Board

Dr Ian Gould
Chancellor
University of South Australia

Dr Andy Barnicoat
Chief, Community Safety & Earth Monitoring Division
Geoscience Australia

Dr Paul Heithersay
Chief Executive Olympic Dam Task Force, and Deputy Chief Executive, Resources and Energy Group, Department of State Development

Dr Jon Hronsky
Principal
Western Mining Services

Dr Phil McFadden
National Geoscience advocate and lobbyist; driver of the UNCOVER initiative

Dr Roric Smith
VP Discovery / Chief Geologist
Evolution Mining

plus the Executive Committee

Participants

Organisations

Administering Organisation

Macquarie University (MQ)

Collaborating Organisations

Curtin University (CU)

University of Western Australia (UWA)

Partners

Australian Partner

Geological Survey of Western Australia (GSWA)
Dr Ian Tyler - CCFS Leader GSWA

International Partners

CNRS and Université de Montpellier, France

Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China

University of Maryland, USA

University of Saskatchewan, Canada

Bayreuth University, Germany

Chief Investigators

Dr Elena Belousova - MQ

Associate Professor Simon Clark - MQ

Professor Marco Fiorentini - UWA

Professor Stephen Foley, Research Coordinator - MQ

Professor William Griffin - MQ

Professor Matt Kilburn - UWA

Professor Zheng-Xiang Li - CU

Professor T. Campbell McCuaig, Node Leader - UWA

Associate Professor Alexander Nemchin - CU

Associate Professor Craig O'Neill - MQ

Professor Suzanne Y. O'Reilly, Director - MQ

Associate Professor Norman Pearson - MQ

Professor Martin Van Kranendonk - University of NSW

Professor Simon Wilde, Node Leader - CU

Associate Professor Yingjie Yang - MQ

Partner Investigators

Australian Partner Investigator

Dr Klaus Gessner - GSWA

International Lead Partner Investigators

Professor Michael Brown - Maryland

Dr David Mainprice - Montpellier

Professor Catherine McCammon - Bayreuth

Professor Fuyuan Wu - CAS Beijing

Associate Investigators

Associate Professor Juan Carlos Afonso - MQ

Dr Olivier Alard - Universite de Montpellier, France/MQ

Associate Professor Christopher Clark - CU

Associate Professor Nathan Daczko - MQ

Professor Simon George - MQ

Dr Richard Glen - MQ Adjunct Professor

Dr Masahiko Honda - Australian National University

Professor Dorrit Jacob - MQ

Associate Professor Chris Kirkland - CU

Professor Jochen Kolb - Geological Survey of Denmark and Greenland

Professor Louis-Noel Moresi - University of Melbourne

Associate Professor Sandra Piazolo - MQ

Professor Steven Reddy - CU

Associate Professor Tracy Rushmer - MQ

Dr Bruce Schaefer - MQ

Professor Paul Smith - MQ

Professor Simon Turner - MQ

Dr Michael Wingate - GSWA

Professor Shijie Zhong - University of Colorado, Boulder, USA

Early Career Researchers (ECR)

Dr Andrea Giuliani - MQ (DECRA)

Dr Yoann Gréau - MQ

Dr Jin-Xiang Huang - MQ

Dr Heejin Jeon- UWA

Dr Crystal LaFlamme - UWA

Dr Yongjun Lu - UWA

Dr Takako Satsukawa - MQ (ECSTAR)

Dr Edward Saunders - MQ

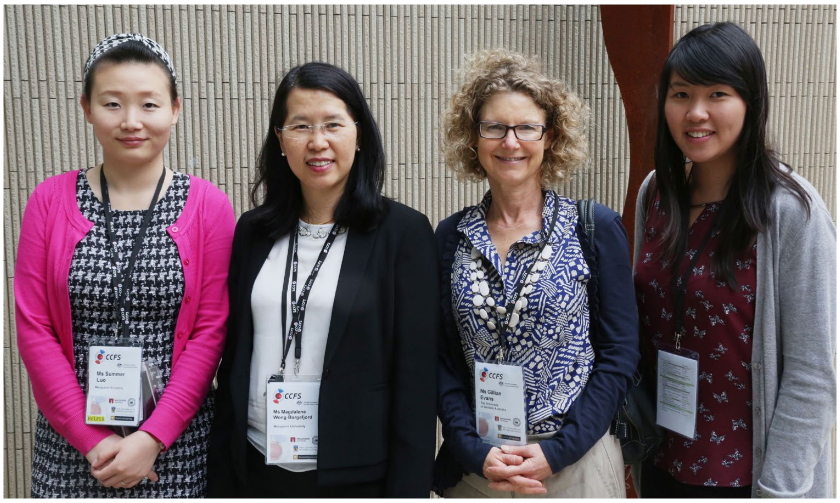
Dr Qing Xiong - MQ

Dr Weihua Yao - CU

Dr Siqi Zhang - MQ

A full list of CCFS participants is given in *Appendix 4* and at http://www.ccfs.mq.edu.au/

Part of the CCFS Administration team L-R: Summer Luo, Magdalene Wong-Borgefjord, Gillian Evans and Rong-Chyi Ngoh.



NEW STAFF

Dr Hadi Shafaii Moghadam joined CCFS in October 2015 as a CCFS funded Research Associate. He completed his PhD degree in Geology-Geochemistry at Shahid Bebeshti University (SBU) at Tehran and Strasbourg University (SU) at France (Scientific joint).

His '*virtual postdoc*' research with R. J. Stern at U. Texas Dallas (2009-2015), was focused on the major issues surrounding the fossilised slices of oceanic lithosphere in SW Asia, using geochemistry, geochronology and geodynamics and emphasising mantle petrology and chromite genesis.

His research interests have mainly focused on the crustal and mantle evolution of SW Asia, including Iran and environs. His main research themes include: 1) Ancient (500-600 Myr) arc magmatism tempos, continental crust growth and identification of hidden 2.5 billion-year old deep crust; 2) Fossilised fragments of ancient oceanic lithosphere, their ages, genesis and their economic aspects; 3) young (ca 40-2 Myr) igneous activity in SW Asia; 4) Mechanisms and triggers for detachment of continental blocks from Gondwana and their accretion to southern Eurasia.

Other new staff *(featured on pp. 12-13 of our ECR section)*

Dr Andrea Giuliani

Dr Heejin Jeon

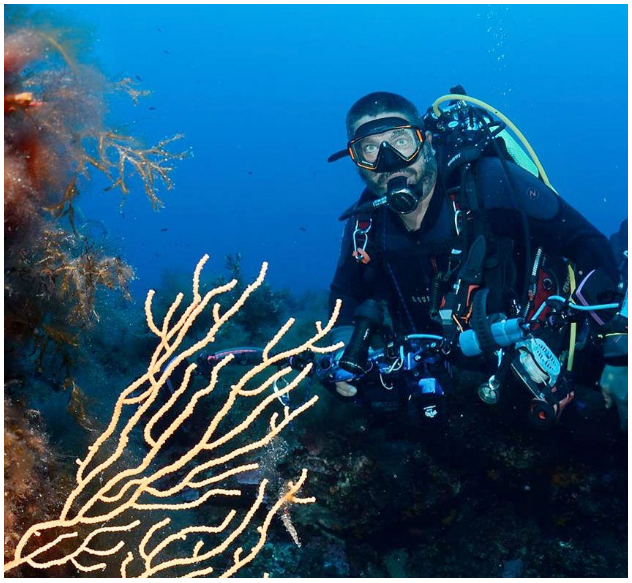
Dr Crystal LaFlamme

Dr Qing Xiong

CCFS FUTURE FELLOWS

The application for the CoE CCFS foreshadowed that such a Centre of Excellence would become an attractor for rising stars and research leaders in relevant disciplines and fields of interest. The success of CCFS participants in the ARC Future Fellow rounds emphasises this role of our Centre in recruiting high-flyers at early to mid-career levels. Nine Future Fellows, Dr Elena Belousova, Professor Marco Fiorentini, Dr Heather Handley, Professor Dorrit Jacob, Associate Professor Craig O'Neill, Associate Professor Sandra Piazolo, Associate Professor Yingjie Yang, Dr Xuan-Ce Wang and Dr David Wacey have projects relevant to CCFS goals and are profiled in the "*Participants*" section of our previous reports (http://www.ccfs.mq.edu.au/AnnualReport/Index.html). Two new Future Fellowships were awarded in 2015 to Dr Olivier Alard and Dr Kate Selway. Kate will commence her fellowship in 2016.

Dr Olivier Alard is a geochemist and petrologist who has developed, over the years, expertise in *in situ* geochemistry of terrestrial and extra-terrestrial mafic and ultramafic rocks. He obtained his Masters degree at Montpellier University in 1994



then moved to Macquarie University for his PhD (1996-2000). His postdoctoral studies in the UK were supported by a Marie Curie EEC grant. He then obtained a Royal Society Fellowship. In 2004, he was hired by the Centre National de la Recherche Scientifique as a full-time researcher in Géosciences Montpellier (France). He obtained his Habilitation to Direct Research (State PhD) in 2015 and was promoted to Research Director the same year.

Olivier's Future Fellowship project aims to investigate the subject of global element cycles in the deep Earth and how they connect to the evolution of the exosphere through the prism of elemental and isotopic fractionation of chalcophile elements (e.g. S, Se, Te, Cu). Using novel integrated elemental and isotopic approaches, Olivier will track the origin and fate of these sentinel elements during accretion and subsequent redistribution in fluids to Earth's surface. This new knowledge is critical to understanding how these and other elements of strategic and economic importance, such as the Platinum Group Elements, are extracted from the deep Earth and transported to the surface.

EARLY CAREER RESEARCHERS (ECR)

The second primary goal of CCFS (see *p. 3*) concerns the recruitment, development and mentoring of Early Career Research (ECR) staff "*for the development of the next generation of Australia's geoscientists*".

The following profiles present 2015 ECRs and summarise their expertise and research areas.

New 2015

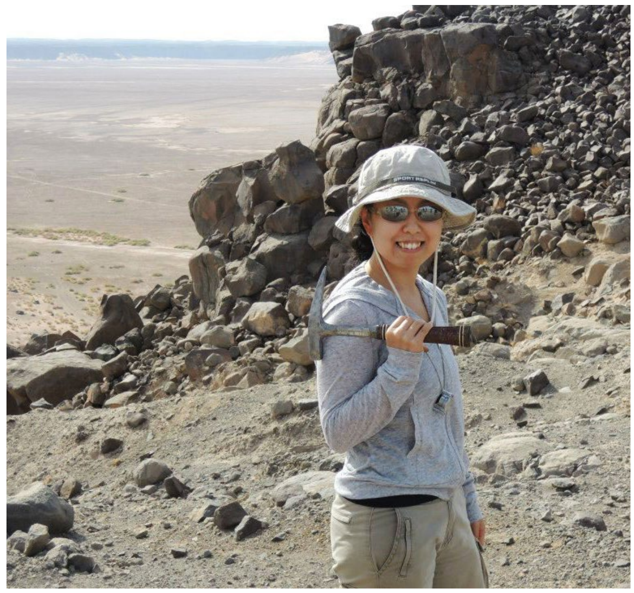
Dr Andrea Giuliani joined the CCFS in June 2015 as an ARC DECRA (Discovery Early Career Research Award) Fellow. Andrea completed his PhD in mantle geochemistry at the University of Melbourne in 2013 where he then undertook a year of post-doctoral research in 2014 before becoming a lecturer in Igneous Petrology in January 2015.

Andrea's research focuses on the composition and sources of deep Earth fluids and melts - including kimberlites, which are

the main source of terrestrial diamonds. Specifically, kimberlites represent the deepest melts that reach the Earth's surface and therefore provide a unique probe into the deepest realms of our planet.

At CCFS, Andrea is working closely with Professors Sue O'Reilly, Bill Griffin and Steve Foley to improve current understanding of the evolution of the Earth's interior and the melting processes affecting it, with particular attention to the role of volatiles and recycled crustal and surface material that trigger deep melting events. See *Research highlight pp. 55-56.*

Dr Heejin Jeon received her Bachelor and Master degrees at the School of Earth and Environmental Sciences, Seoul National



University. She was then awarded a PhD at the Research School of Earth Sciences, Australian National University (2012). Her PhD project focused on continental crust evolution and crustal recycling in southeastern Australia (Carboniferous-Permian granites across the Lachlan Fold Belt and New England Orogen). During her time at ANU, Heejin worked extensively on zircon for U-Th-Pb dating, O and Hf isotope measurements (SHRIMP II and LA-MC-ICPMS). She then had two years of postdoc experience in the NORDSIM ionprobe lab, Swedish Museum of Natural History, where she expanded her ion probe expertise through the use of the CAMECA IMS1280 and contributed to a wide variety of collaborative projects. She also carried out a project in the Neoproterozoic Arabian Shield and studied how much this previously-known-as-juvenile-crust is contaminated by older crustal materials. Heejin is now working at the Ion Probe Facility, CMCA, University of Western Australia, with CCFS participants Matt Kilburn and Laure Martin, to improve widely used isotope applications and also to develop new applications.

Dr Crystal LaFlamme is Canadian and attended Acadia University for her BSc. She completed her MSc at Memorial University of Newfoundland studying the tectonostratigraphy and formation of volcanic rocks of the Makkovik Province in

northern Labrador. Her PhD at the University of New Brunswick investigated the formation and geodynamic evolution of a reworked Archean high-grade terrane in the Western Churchill Province in the Canadian Arctic.

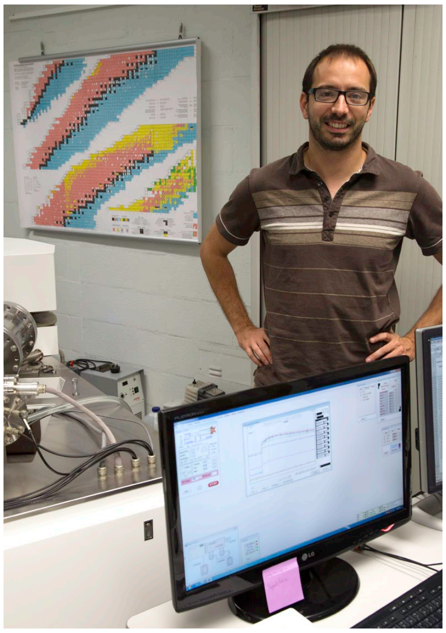
She joined CCFS as a postdoctoral Research Associate in February 2015 to study the sulfur isotope record of craton margins at the Centre for Exploration Targeting, University of Western Australia. Her research focuses on anomalous sulfur isotope signatures preserved in the Archean-Proterozoic rock record. Crystal is leading the development of a suite of reference materials for *in situ* multiple sulfur isotope analysis of magmatic and hydrothermal ore deposit sulfides. Early sulfur and lead isotope results demonstrate that sulfur and metals in certain Proterozoic ore deposits are being sourced from metal-endowed Archean cratons. This knowledge base is building to ultimately better understand the link between fluid-driving tectonic processes and ore genesis. Her research contributes to CCFS Flagship Program 4. See *Research highlight pp. 36-37.*

Dr Qing Xiong completed his undergraduate studies at China University of Geosciences (Wuhan), and joined CCFS in 2011 as a Cotutelle PhD candidate. He received PhD degrees from China University of Geosciences (Wuhan) in December 2014 and from Macquarie University in November 2015. Qing's PhD project focused on the origin and evolution of orogenic peridotites and ophiolites from Tibet (China), and revealed the detailed upper-mantle processes and subduction geodynamics during the assembly of the Tibetan-Himalayan Plateau in the Phanerozoic, using conventional and cutting-edge methodologies. His PhD studies trained him as an independent researcher, and produced five first-authored publications in high-impact international journals as well as several manuscripts prepared for submission.

Qing commenced his employment as a Research Associate at CCFS, Macquarie University in June 2015. His current research focuses on the ophiolitic mantle rocks in the Yarlung Zangbo Suture Zone of South Tibet as part of targets of CCFS Flagship Program 1, TARDIS II. He is planning to carry out systematic sampling and petrochemical characterisation of the mantle sections, before investigations of their deformation patterns using Electron Backscattered Diffraction (EBSD). The study will provide new insights into mantle recycling processes in subduction and collision zones and the genesis of metal ore deposits (e.g., chromitites). See *Research highlight pp. 63-64.*

Continuing

Dr Yoann Gréau joined GEMOC, MQ in 2007 as a PhD candidate (graduated 2011) after obtaining an MSc from the University of Montpellier II (France), where he trained in ultramafic petrology and geochemistry, studying ultra-refractory abyssal peridotites. During his PhD studies, he investigated the origin and history of eclogite xenoliths brought up from the lithosphere-asthenosphere boundary by kimberlitic magmas. His research focused on the petrology and geochemistry of the sulfide phases, looking at siderophile and chalcophile elements (e.g. Cu, Ni, Se, Te, PGEs and S isotopes). He also investigated the relationships between microstructures and mineral geochemistry (e.g. REE, HFSE, LILE and O isotopes) of the main silicate phases, demonstrating strong links between mantle eclogites and metasomatic processes occurring within the sub-continental lithospheric mantle.



From 2013 to June 2015 Yoann co-managed the *TerraneChron*® team in CCFS. *TerraneChron*® uses a specifically developed methodology to study the evolution of the continental crust through time by using integrated *in situ* analysis of zircons for U-Pb ages and O- and Hf-isotope composition. The methodology, developed at Macquarie University, has had great success with our industrial and geological survey partners.

Since July 2015 his Research Associate role, as part of the CCFS Technology Development Program *"GAU multi-instrument development - Frontiers in integrated laser-sampled trace-element and isotopic geoanalysis"*, is to provide high-quality research related to the development of innovative methods for *in situ* analysis of trace elements, radiogenic isotope and non-conventional stable isotope systems by laser ablation ICP-MS. In particular, he will focus on promoting advancement of geochemical methodologies and techniques involving Femtosecond laser and the new Nu Plasma II Multi-Collector ICP-MS (MC-ICP-MS) recently installed at the GAU (July 2015). His research also contributes to CCFS Flagship Program 1.

Dr Jin-Xiang Huang completed her undergraduate study at China University of Geosciences, Beijing as one of the top students in her class. She received her PhD from Macquarie

University in December 2011 studying the metasomatism and origins of xenolithic eclogites from the Roberts Victor kimberlite, South Africa. This provided her with extensive experience in the clean labs, on state-of-art instruments producing precise geochemical data, and integrating a wide range of information into a coherent model. She discovered that mantle metasomatism has completely changed the petrography and chemical and isotopic compositions of most eclogites; therefore, evidence from these can no longer be used to support the popular idea that they represent subducted oceanic crust. Information from the few unmetasomatised eclogites favours their origin from deep-seated magmas.

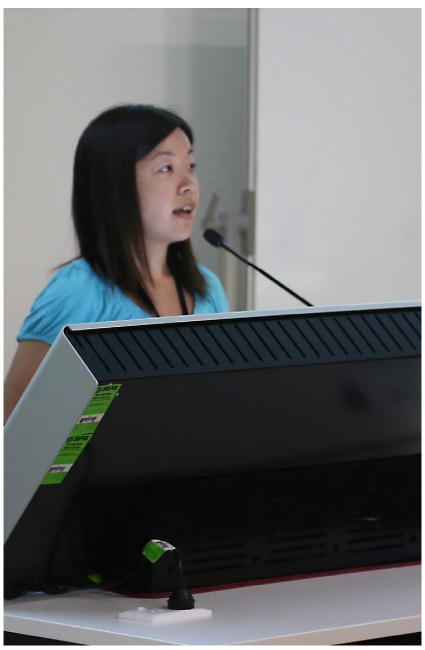
After completing her PhD, Jin-Xiang joined CCFS as a Post-doctoral Research Associate, to work on the stable isotope and water contents of mantle rocks (both eclogites and peridotites) and in different mantle processes (e.g. magma crystallisation, mantle metasomatism). This will provide a better understanding of mantle processes and further constraints on geodynamics.

In 2015, she worked on Mg and O isotopes in Roberts Victor eclogites and found that these two isotopic systems are decoupled during progressive mantle metasomatism by carbonatitic to kimberlitic melts/fluids. The eclogites that interacted with carbonatitic melts/fluids largely retained the Mg-isotope compositions of their protoliths, but their O-isotope compositions were heavily modified. In the samples that reacted with kimberlitic melts/fluids, the isotope compositions of both Mg and O have been modified. The large variation of $\delta^{26}Mg$ combined with low $\delta^{18}O$ in fresh eclogites does not show clear signatures of oceanic crust-related processes, indicating that the subduction origin model for Roberts Victor eclogites is at least questionable. In a separate project, she was involved in developing standards for the *in situ* (SIMS) analysis of Si and C isotopes of mantle-derived moissanite (SiC). She also analysed several suites of this phase from localities worldwide, to help understand the development of low oxygen fugacity in the upper mantle. Her research contributes to CCFS Flagship Program 1.

Dr Yongjun Lu is currently the Senior Geochronologist at the Geological Survey of Western Australia (GSWA) and an Adjunct Senior Research Fellow at the Centre for Exploration Targeting

(CET), UWA. Before joining GSWA in July, 2015, Yongjun was a postdoc at CET funded by CCFS. Together with manager Dr Michael Wingate at GSWA, Yongjun is now ensuring that about 80 samples from WA are dated by SHRIMP every year, contributing to a fantastic world-class geochronological dataset for WA. Such high-quality data is the foundation for understanding Earth's evolution and mineral resources formation. Yongjun is also in charge of the isotopic programs at GSWA such as Sm-Nd, Lu-Hf and O isotopes, which are used to tackle various scientific questions such as imaging the lithospheric architecture through cover, understanding crustal evolution and mineral deposit formation. In addition, Yongjun is leading a project at GSWA investigating zircon chemistry of Archean granitoids and is involved in a new project unveiling the geology of the Southwest Terrane of the Yilgarn Craton. Through CCFS, Yongjun has an ongoing collaboration with the Chinese Academy of Geological Sciences (CAGS) and China University of Geosciences in Beijing (CUGB) to investigate the porphyry copper systems in the Tibetan plateau and surrounding regions. Yongjun also serves as reviewer for prestigious international journals such as *Geology, Journal of Petrology, Chemical Geology, Economic Geology, Lithos, Gondwana Research, Mineralium Deposita and Ore Geology Reviews.*
See *Research highlights pp. 41-42, 45, 57, 72-73.*

Dr Takako Satsukawa joined CCFS/GEMOC in October 2012 as an ECSTAR (Early-Career Start-up Award Researcher) funded by an ARC Centre special grant to CCFS for early-career researchers. She completed her PhD jointly at Shizuoka University (Japan) and the Université Montpellier (France). Her dissertation research focused on microstructural and petrological characteristics of mantle-derived peridotite xenoliths in basaltic rocks and their implications for the evolution and seismic anisotropy of the uppermost mantle beneath the back-arc region. She mastered the application of Electron Backscatter Diffraction (EBSD) technology to measure the crystallographic preferred orientations (CPO) of individual grains of minerals. Her current research interests include the rheology of the uppermost mantle and the history of the roots of ancient continents to provide new constraints on the rheological properties of the lithospheric mantle.



Her research interests also lie in developing a systematic approach to mapping the behaviour of melts and fluids in the upper mantle. Takako approaches this by combining microstructural analysis, geochemical analyses, analysis of water contents, and numerical modelling of the seismic properties of peridotite xenoliths and chromitite from different lithospheric levels which have experienced different degrees of melt-fluid-rock interaction. Since previous work by GEMOC has used geochemical analysis, a new methodology for mapping '*hidden*' microstructures can be developed by combining these approaches.

In 2015 she studied the microstructures of chromitite from the Luobusa peridotite (E. Tibet). The chromite grains showed exsolution of diopside and SiO_2, suggesting previous equilibration in the Mantle Transition Zone (MTZ; 410-660 km deep). The EBSD analysis identified strong crystallographic preferred orientation in both the chromite and small olivine inclusions, interpreted to reflect crystal-plastic deformation of fine-grained aggregates of CF-structured chromite and waddsleyite in the MTZ. This work, the first to define the tectonics of the MTZ, was published in *Nature Scientific Reports* (*CCFS Publication #673*), is part of CCFS Themes 2 and 3, Earth's Evolution, and Earth Today and contributes to CCFS Flagship Program 1. See *Research highlight pp. 53-55*.

Dr Edward Saunders completed his PhD with CCFS/GEMOC in 2013. His thesis investigated the petrography and geochemistry of sulfides hosted in mantle peridotites and pyroxenites, with an emphasis on their gold concentration. He continued to work on this research when he commenced employment as an Associate Lecturer at Macquarie University in 2014.

In July 2015, Ed became the manager of the *TerraneChron*® team at CCFS. This role involved integrating *in situ* analysis of U-Pb, Hf-isotope and trace element concentrations in zircons and involved collaboration with a number of industry and geological

survey partners. This methodology has provided valuable insight into geological mapping and exploration programs. In 2015, *TerraneChron*® imaged and analysed 1817 grains of zircons for a total of 6 different projects from Asia and Australia.

In December 2015, Ed took up the position of Lecturer in the School of Environmental & Rural Science at the University of New England.

Dr Weihua Yao received her doctoral degree from Curtin University in July 2014, studying the tectonostratigraphic evolution of the Ediacaran-Silurian Nanhua Basin and the nature of the lower Paleozoic Wuyi-Yunkai orogeny in South China. Since then she has worked as a Postdoctoral Research Associate with CCFS, TIGeR, ACTER and IGCP 648 at Curtin University, under CCFS Flagship Program 5. Her research has mainly focused on sedimentary and provenance correlations between the Indian-Australian Gondwana and Asian continents/terranes (including South China and Indochina blocks), and also the Precambrian paleogeography of Hainan Island in the supercontinents Nuna

and Rodinia. Two main highlights of her research suggest an Ediacaran-Cambrian collision between South China and northern India, leading to the formation of the Nanhua foreland basin and the Wuyi-Yunkai orogeny in South China; and Hainan Island's connection with western Laurentia, in which Hainan probably provided detritus to rift basins/grabens in the neighbouring western Laurentia and Tasmania during the Nuna breakup; and to foreland basins in the neighbouring western Laurentia, Tasmania and western Yangtze during the Rodinia assembly. Weihua is also leading a China Geological Survey funded project, investigating the Ediacaran-Silurian basin on the western Yangtze margin. Her work led to the publication of five papers and more are in the pipeline.

Dr Siqi Zhang completed his undergraduate study at Peking University, Beijing, and graduated with a PhD from the University of the Chinese Academy of Science (July 2011). He then took up

a postdoctoral fellowship at University of Chinese Academy of Science from 2011 to 2013. His research focused on using high performance computation with high resolution models to solve different geodynamic problems.

Siqi joined CCFS as a Postdoctoral Research Associate in April 2013. Since then, his research has focused on using high resolution numerical models to study planetary evolution. He built mantle-core coupling models to study the early evolution of Mars. By exploring a range of uncertainties with different model settings, the results suggest that mobile-lid may exist in early Martian history, and it is the likely cause of an early dynamo. He is also exploring the construction of an Earth mantle-flow model constrained by plate motion in the past few hundred million years to recover the mantle structure and to track its evolution over that time. He has also developed a new treatment of magmatism in global mantle flow models. This treatment includes melt depletion and solid matrix compression due to melt extraction, which not only better simulates the melt process but also makes tracking of crustal generation possible. In addition, he is involved in developing high performance SPH (smoothed particle hydrodynamics) code using Intel Xeon Phi co-processor to study the process of planetary formation. His research contributes to CCFS Flagship Program 3.

The CCFS research program

The CCFS CoE builds on world-class infrastructure and world-leading research expertise and track record, and has already multiplied the capabilities of the Collaborating and Partner Institutions. The research program aims to enhance existing strengths in geology, geochemistry, geophysics, experimental petrology and petrophysical/dynamic modelling, and to integrate knowledge and datasets from these disparate fields.

Major Research Objectives

- **to determine, using constraints from Earth's oldest crust and mantle, lunar samples and meteorites, the role of fluids in creating a dynamic planet**
- **to understand how Earth's core-mantle system and its interaction with fluids have produced periodic cataclysms and controlled the evolution of the crust, hydrosphere and atmosphere**
- **to develop new approaches to petrophysical and dynamic modelling, integrating geophysics, geodynamics and geochemistry**
- **to develop an integrated Earth model linking tectonics, internal structure and dynamics, and the fluid-mediated transport of mass and energy from the interior to the surface**
- **to develop new approaches to interpreting geophysical imagery, for application to basic science and resource exploration**
- **to develop a new understanding of the timing and distribution of giant resource systems, based on a new level of understanding of Earth's fluid plumbing systems, processes and dynamics**
- **to undertake the strategic, frontline developments in hardware, analytical methodologies, theory and software technology that are required to fulfil the research goals**

These objectives are being addressed through the Research Programs described below.

The scope of the research, and thus of the research programs, are determined by the funding base allocated by ARC with strategic leverage planned to expand available resources.

FLAGSHIP RESEARCH PROGRAMS

The original Foundation Programs for 2011-2014 were funded from the ARC Centre funds allocation, and included components from the Universities' funding support. Programs were chosen from formal applications by CCFS participants based on presentations and discussions at a 2-day meeting in October 2010, ratified by the Executive Committee, and accepted on report to the Advisory Board. The Programs were designed to be interdisciplinary, cross-nodal and to foster early-career/postgraduate researcher's participation. Research directions were designed to contribute to the overarching three major Themes identified to bring about a new level of understanding of Earth and its resource dispersion. They included three integrated projects targeted at Technology Development.

In 2014 the Flagship Programs were restructured to identify the most productive research directions relevant to fulfilling the CCFS vision of "*Delivering the fundamental science needed to sustain Australia's resource base.*" All the research programs were scrutinised, reassessed and realigned (following advice from the Science Advisory Committee).

This resulted in seven Flagship Programs (see *p. 18*) based on the benchmark outcomes of the first 3 years and extending in new directions; programs that had come to fruition in the first three years were finalised. These Flagship Programs target the research goals through to 2018, providing a new focus and realigned strategies to deliver more transformational outcomes and leave a legacy in knowledge, new technology and methodologies, and vital new knowledge about Australia's geological evolution to guide smart new mineral exploration. They are underpinned by two Technology Development Programs designed to deliver more leading-edge geochemical breakthroughs, capitalising on the outstanding geochemical instrumental infrastructure across CCFS.

Aims and progress are detailed in *Appendix 1*.

***Appendix 2* presents the 2016 workplan.**

Independently funded basic research projects are listed in *Appendix 3*.

2014 FLAGSHIP PROGRAMS

Program	Coordinator and main Centre personnel
1. Deep Earth fluids in collision zones and cratonic roots (TARDIS II) Themes 1, 2, 3 Earth Fluids, Earth Architecture	**O'Reilly**, **Griffin**, Pearson, Kilburn, Martin, Huang (ECR), Satsukawa (ECSTAR, ECR), Gréau, Saunders (ECRs) McGowan, Xiong, Xu, Tilhac, Colas, Lu, Liptai, Chasse (PhDs)
2. Genesis, transfer and focus of fluids and metals Themes 2 and 3 Earth Fluids	**Fiorentini**, McCuaig, Foley, O'Reilly, Griffin, Reddy, Rushmer, Adam, Turner, Lu (ECR), Bagas, Gorczky, Piazolo, Kilburn, Clarke Bjorkman, Iaccheri, Stevenson, Davies, Dering, Poole, Bennett, Lampinen (PhDs), Poh (Masters)
3. Modelling fluid and melt flow in mantle and crust Themes 2 and 3 Earth Fluids, Earth Architecture	**O'Neill**, Afonso, Yang, Li, Foley, Clark, S. Zhang (ECR), Shan, Gorczky, Smith, O'Reilly, Griffin Wasilev, Ramzan, Oliviera, Grose, Jiang (PhDs)
4. Atmospheric, environmental and biological evolution Theme 1 Earth Fluids, Earth Architecture	**Van Kranendonk**, Wacey, Fiorentini, Foley, McCuaig, Cliff, Kilburn, Grange, Kirkland, Alard, LaFlamme Baumgartner, Selvaraja, Barlow, Pearse (PhDs), Djokic, Blake, Gogouvitas, Tadbiri (MPhils), Dang (Honours)
5. Australia's Proterozoic record in a global context Themes 2 and 3 Earth Architecture	**Li**, Pisarevsky, Wang, Yao (ECR), Wingate, O'Reilly, Griffin, Pearson, Belousova, McCuaig Tao, Stack, Y. Liu (PhDs), Chamberlain (Honours)
6. Fluid regimes and composition of early Earth Themes 1 and 3 Earth Fluids, Earth Architecture	**Wilde**, Nemchin, Grange, Martin, O'Neill Ge (PhD)
7. Precambrian architecture and crustal evolution in WA Themes 1, 2 and 3 Earth Architecture	**Gessner**, Kirkland, Belousova, Gréau, Yuan, Merdie, Wingate, Tyler, Lu Derring (PhD)

TECHNOLOGY DEVELOPMENT

Cameca Ion microprobe development Themes 1, 2 and 3 Earth Fluids, Earth Architecture	**Kilburn**, Martin, Jeon, Fiorentini, McCuaig, Wacey, Griffin, LaFlamme, Reddy Students of CIs and ECRs utilising the Ion Probe Facility are active in the program
GAU multi-instrument development Themes 1, 2 and 3 Earth Fluids, Earth Architecture	**Pearson**, Griffin, O'Reilly, Gréau (ECR), Kilburn, Martin, Huang (ECR), Saunders (ECR) McGowan, Gao, Xiong (PhDs)

Where out of this world is CCFS?

As part of our quest to better understand the processes that led to the formation of the early Earth, CCFS has been investigating the early history of both the Moon and Mars. **See *Research highlight p. 52-53.***

Moon

Mars

WHERE IN THE WORLD IS CCFS?

Solonker suture zone, Inner Mongolia.

Great Serpentinite Belt, New England Region, Australia.

Cabo Ortegal, Galicia, Spain.

The Yilgarn, WA, Australia.

Penghu Basalts, Penghu Islands, Taiwan.

Xigaze ophiolite complex southern Tibet, China.

Communications 2015

CCFS web resources (http://ccfs.mq.edu.au/) provide information on background, research and downloadable files of the Annual Report and Research highlights.

Links to the GEMOC website (http://www.gemoc.mq.edu.au/) provide past GEMOC Annual Reports, updated details on its methods, new analytical advances and software updates (GLITTER), activities of research teams within GEMOC, synthesised summaries of selected research outcomes and items for secondary school resources.

Links to the CET (Centre for Exploration Targeting) website (http://www.cet.edu.au/) provide access to wider information about CET activities beyond its involvement in CCFS and especially the wide base of end-user interaction.

Links to The Institute for Geoscience Research (TiGer) website (http://tiger.curtin.edu.au/) provide information about their facilities, participants and research activities.

Strong industry interaction in CCFS in 2015 ranged from presentations to specific industry groups in their offices to numerous formal and informal workshops at CET and GEMOC, and invited and plenary presentations at peak industry symposia, workshops and conferences nationally and internationally.

CCFS publications for 2015 are given in Appendix 5.

The 188 CCFS publications that were published in 2015 are dominantly in high-impact international journals (Thomson ISI); the remainder are in outlets targeted to specific stakeholders (e.g., Australian Journal of Earth Sciences, Economic Geology).

CCFS now has a LinkedIn Group - Join the conversation at http://www.linkedin.com/groups/6969996

PARTICIPATION IN WORKSHOPS, CONFERENCES AND INTERNATIONAL MEETINGS IN 2015

CCFS Investigators, associated staff, early-career researchers and postgraduates had a high profile at 35 peak geophysical, metallogenic, geodynamic and geochemical conferences as convenors, invited speakers, or presenters, with 212 presentations including:

- 4th Australasian Universities Geoscience Educators Network (AUGEN) Meeting, Melbourne, Australia, 12-13 January 2015
- ASEG-PESA 24th International Geophysical Conference and Exhibition, Perth, Australia, 15-18 February 2015
- 13th Biennial AMAS Australian Microbeam Analysis Symposium, Hobart, Australia, 11-13 February 2015
- WA Geophysics Workshop, Perth, Australia, 18 February 2015
- 46th Lunar and Planetary Science Conference, The Woodlands, TX, USA, 16-20 March 2015
- Chinese Academy of Sciences (IGG-CAS), Beijing, China, 30 March 2015
- European Geosciences Union (EGU), Vienna, Austria, 12-17 April 2015
- 2015 Joint Assembly: Canadian Cratons Through Time: 4.0 Ga of Chemical Evolution and Tectonism, Montreal, Canada, 3-6 May 2015
- AGU-GAC-MAC Joint Assembly, Montreal, Canada, 3-7 May 2015
- WA, Multiscale Seismic Workshop, ARRC, Perth, Australia, 19 May 2015
- Astrobiology Science Conference 2015, Habitability, Habitable Worlds and Life, Chicago, USA, 15-19 June 2015
- World Chinese Geoscience Conferences, Academia Sinica, Taipei, Taiwan, 15-21 June 2015
- Inaugural Advanced Resource Characterisation Facility Conference, Perth, Australia, 18 June 2015
- 78th Annual Meeting of the Meteoritical-Society, Berkeley, CA, USA, 27-31 July 2015
- Microscopy and Microanalysis 2015, Portland, USA, 2-6 August 2015
- Saying goodbye to a 2D Earth, International Conference, Margaret River, WA, Australia, 2-7 August 2015
- 12th Annual Meeting Asia Oceania Geosciences Society (AOGS), Singapore, 2-7 August 2015
- 2nd Mars 2020 Landing Site Workshop, Monrovia, California, USA, 4-6 August 2015
- IGCP-649 Workshop on: Ophiolites and Related High-Pressure Rocks in the Qilian Mountains, Xining, China, 5-10 August 2015

Romain Tilhac at the Goldschmidt Conference.

- 2015 Goldschmidt Conference, Prague, Czech Republic, 16-21 August 2015

- 13th SGA Conference, Nancy, France, 24-27 August 2015
- 2nd European Mantle Workshop, Wroclaw, Poland, 24-28 August 2015
- International Conference Large Igneous Provinces, Mantle Plumes and Metallogeny in the Earth's History, Irkutsk-Listvyanka, Russia, 1-8 September 2015
- 8th Hutton Symposium on Granites and Related Rocks, Florianópolis, Brazil, 20-25 September 2015
- First China-Russia International Meeting on the Central Asian Orogenic Belt and IGCP 592 Workshop, Beijing, China, 23-25 September 2015
- TIGeR Conference, Curtin University, Perth, Australia, 23-25 September 2015
- SEG 2015: World-Class Ore Deposits: Discovery to Recovery, Hobart, Australia, 27-30 September 2015
- 15th Australian Space Research Conference, Canberra, ACT, Australia, 29 September - 1 October 2015
- Geological Society of America Meeting, Baltimore, Maryland, USA, 1-4 November 2015
- 2nd Lithosphere Dynamics Workshop, Perth, Australia, 19-20 November 2015
- Specialist Group in Tectonics and Structural Geology (SGTSG) conference: Riding the Wave, Caloundra, Queensland, Australia, 22-27 November 2015
- Geological Survey of Western Australia 2015 Annual Lectures, Perth, Australia, 3 December 2015
- Greenland Day Conference, Perth, Australia, 9 December 2015
- 59th Annual Meeting of the Palaeontological Association, Cardiff, UK, 14-17 December 2015
- AGU Fall Meeting, San Francisco, USA, 14-18 December 2015

INVITED TALKS AT MAJOR CONFERENCES AND WORKSHOPS IN 2015

ASEG-PESA 24th International Geophysical Conference and Exhibition, Perth, Australia, 15-18 February 2015	Geoscience data integration: Insights into mapping lithospheric architecture G.C. Begg, **W.L. Griffin**, **S.Y. O'Reilly** and **L. Natapov** **Keynote**
13th Biennial AMAS Australian Microbeam Analysis Symposium, Hobart, Australia, 11-13 February 2015	Quantitative microstructural analysis of geological materials: New views on glacier flow, meteorite impacts and deep mantle processes **S. Piazolo** **Invited**
WA Geophysics Workshop, Perth, Australia, 18 February 2015	Large scale issues in the WA lithosphere **H. Yuan** **Invited**
WA, Multiscale Seismic Workshop, ARRC, Perth, Australia, 19 May 2015	Passive seismic studies in the Capricorn orogen **H. Yuan** **Invited**
World Chinese Geoscience Conferences, Academia Sinica, Taipei, Taiwan, 15-21 June 2015	Supercontinent-superplume coupling in Earth history: toward a new tectonic paradigm **Z.X. Li** **Invited**
Inaugural Advanced Resource Characterisation Facility Conference, Perth, Australia, 18 June 2015	High-impact atom probe research: A case study on shocked zircon **S.M. Reddy** **Invited** The NRSP's Geoscience Atom Probe: Context and future research **S.M. Reddy** **Invited**
78th Annual Meeting of the Meteoritical-Society, Berkeley, CA, USA, 27-31 July 2015	Record of the early impact history of the Earth-Moon system: targeted geochronology of shocked zircon N.E. Timms, **S.M. Reddy**, A.J. Cavosie, **A.A. Nemchin**, **M.L. Grange** and T.M. Erickson **Invited**

INVITED TALKS *cont...*

12th Annual Meeting Asia Oceania Geosciences Society (AOGS), Singapore, 2-7 August 2015	Heterogeneous crust in the Western Australian Craton: Seismic characteristics and tectonic implications **H. Yuan** **invited**
2015 Goldschmidt Conference, Prague, Czech Republic, 16-21 August 2015	Geochronology of *ex situ* shocked zircons: Towards dating impacts A.J. Cavosie, **S.M. Reddy**, N.E. Timms, **T.M. Erickson** and M.R. Pincus **Invited** To subduct or not to subduct? that is the Archaean question… V. Debaille, **C. O'Neill** and A.D. Brandon **Invited** Timescales of magma transfer, degassing and crustal assimilation at Merapi Volcano, Indonesia R. Gertisser, **H. Handley**, M. Reagan, K. Preece, K. Berlo, J. Barclay and R. Herd **Invited** New insights into the lithospheric and deeper mantle **W.L. Griffin**, **J.C. Afonso**, **T. Satsukawa**, **N. McGowan**, **N. Pearson** and **S.Y. O'Reilly** **Invited** Constraints from Sr-Nd-Hf-Pb-Os isotopes for enriched and depleted Hawaiian Plume components in the oldest Emperor Seamounts K. Hoernle, **B. Schaefer**, M. Portnyagin, F. Hauff and R. Werner **Invited** Metallic lead nanospheres discovered in ancient Antarctic zircons M. Kusiak, D. Dunkley, M. Whitehouse, **S. Wilde**, R. Wirth and K. Marquardt **Invited** The evolution of the Hadean Earth **C. O'Neill** **Keynote** Variations in intraplate melting regimes during Earth's evolution **C. O'Neill** and **S. Zhang** **Invited** Cratons, metasomatism and metallogeny **S.Y. O'Reilly**, **W. Griffin**, **N. Pearson**, G. Begg and J. Hronsky **Invited** The Tonga-Kermadec arc - Lau back-arc: recent progress and future research directions **S. Turner** **Keynote**
2nd European Mantle Workshop, Wroclaw, Poland, 24-28 August 2015	Geodynamic and geophysical consequences of stealthy mantle metasomatism **S.Y. O'Reilly**, **W.L. Griffin** and **N.J. Pearson** **Invited**
TIGeR Conference, Curtin University, Perth, Australia, 23-25 September 2015	The chemical signature of syn-deformational fluid-rock interaction: Nano- to microscale **S. Piazolo** **Invited**
SEG 2015: World-Class Ore Deposits: Discovery to Recovery, Hobart, Australia, 27-30 September 2015	Sulfur and metal fertilization of the lower continental crust **M.L. Fiorentini**, M. Locmelis, **J. Adam**, **T. Rushmer**, F. Zaccarini, G. Garuti, Z. Vukmanovic, S. Caruso, M. Moroni, S. Barnes, **S. Reddy** and B. Godel **Invited**
15th Australian Space Research Conference, Canberra, ACT, Australia, 29 September - 1 October 2015	Early Earth and the making of mankind: Astrobiology in our own backyard **M.J. Van Kranendonk** **Plenary Speaker**
Geological Society of America Meeting, At Baltimore, Maryland, USA, 1-4 November 2015	Precambrian reidite unearthed **S.M. Reddy**, T. Johnson, W. Rickard, A. van Riessen, S. Fischer, R. Taylor, T. Prosa, D. Reinhard, K. Rice and Y. Chen **Invited**

2nd Lithosphere Dynamics Workshop, Perth, Australia, 19-20 November 2015	Crust-mantle interactions in hot orogens characterised by counterclockwise P-T-t paths and slow cooling **M. Brown** **Invited** Sulfur and metal fertilization of the lower continental crust **M. Fiorentini** **Invited** Evolution of the lithospheric mantle by melt/rock interaction and its effects on the composition of lithosphere-derived volcanic melts **S. Foley** **Invited** Constraints on kimberlite ascent mechanisms revealed by phlogopite compositions in kimberlites and mantle xenoliths **A. Giuliani** **Invited** Neutral-buoyancy rule over-ruled: Crustal underplating by buoyant magmas during orogeny **R. Loucks** **Invited** Secular change in Archean crust formation recorded in Western Australia **H. Yuan** **Invited**
Geological Survey of Western Australia 2015 Annual Lectures, Perth, Australia, 3 December 2015	Inferring past and current tectonic activities using earthquake seismology **H. Yuan** **Invited**
AGU Fall Meeting, San Francisco, USA, 14-18 December 2015	Petrologically-constrained thermo-chemical modelling of cratonic upper mantle consistent with elevation, geoid, surface heat flow, seismic surface waves and MT data A. Jones and **J. Afonso** **Invited** An early, transient, impact-driven tectonic regime in the Hadean **C. O'Neill**, S. Marchi and **S. Zhang** **Invited** Interactions among mid-ocean ridges, plumes and Large Igneous Provinces J. Whittaker, **J. Afonso**, S. Masterton, D. Müller, P. Wessel, S. Williams and M. Seton **Invited**

OTHER CONFERENCE ROLES

A full list of abstracts for Conferences and Workshops attended is given in Appendix 6 and on the CCFS website.

12th Annual Meeting Asia Oceania Geosciences Society (AOGS), Singapore, 2-7 August 2015	*Session Convener:* **Yingjie Yang** - Seismic Imaging of the Earth's Interior: Methods and Applications
Saying goodbye to a 2D Earth, International Conference, Margaret River, WA, Australia, 2-7 August 2015	*Member of Organising and Scientific Committee:* **Klaus Gessner**
2015 Goldschmidt Conference, Prague, Czech Republic, 16-21 August 2015	*Session Co-Convener:* **Martin Van Kranendonk** - 06i: Modern and Past Microbialites: How do They Form? What Have We Learnt? *Session Co-Convener:* **William Griffin** - 12b: Processes and Deposits of Ultramafic-Mafic Magmas Through Space and Time *Session Co-Convener:* **Andrew Putnis** - 14g: Equilibrium Versus Disequilibrium States in Biologic Hard Tissues and Biomimetic Analogues

OTHER CONFERENCE ROLES *cont...*

2015 Goldschmidt Conference, Prague, Czech Republic, 16-21 August 2015 *cont...*	*Session Co-Convener:* **Martin Van Kranendonk** - 18b: Earth's Early Crust and the Evolution of Plate Tectonic Processes *Session Co-Convener:* **Michael Brown** - 18e: Models for Continental Growth Four Decades On *Session Co-Chair:* **Simon Wilde** - 18f: Not Just for Geochronology Anymore: What Zircon Chemistry and Geochronology Can Tell Us About Thermal Environments, Fluids and Melts in Silicate Crusts *Session Co-Convener:* **Andrea Giuliani** - 20f: Mantle-Derived Intraplate Magmas, their Xenolith and Diamond Cargo: Processes, Timescales, and Geodynamic Implications *Theme Co-Organiser:* **Tracy Rushmer** - 22: Early Earth: Earth's History Before the Phanerozoic *Session Co-Convener:* **Tracy Rushmer** and **Martin Van Kranendonk** - 22d: Mantle Thermal Peaks, Crustal Growth and the Inception of Plate Tectonics
13th SGA Biennial Meeting, Nancy, France 24-27 August 2015	*Session Co-Convener:* **Marco Fiorentini** - 6: Magmatic (Ni-Cu-Cr-PGE) Mineral Systems: Ore Forming Processes and Geodynamic Setting
SEG 2015: World-Class Ore Deposits: Discovery to Recovery, Hobart, Australia, 27-30 September 2015	*Panelist:* **Cam McCuaig** - Pre-Conference Student Mentoring Forum
AGU Fall Meeting, San Francisco, USA, 14-18 December 2015	*Session Co-Convener/Chair:* **Yingjie Yang** - S13A: Bridging the Moho: Joint Imaging of Crust and Lithospheric Mantle Structure II Posters *Session Primary Convener:* **Huaiyu Yuan** - T11B: Characterizing Cratons and Craton Margins I Posters *Session Co-Conveners/Chairs:* **Klaus Gessner** and **Chris Kirkland** - T11B: Characterizing Cratons and Craton Margins I Posters *Session Primary Convener/Co-Chair:* **Zheng Xiang Li** - T13A: How Earth Works 100 Years after Wegener's Continental Drift Theory: Supercontinent Cycles, Plate Tectonics, and Global Geodynamics I Posters *Session Primary Convener:* **Huaiyu Yuan** - T21F: Characterizing Cratons and Craton Margins II *Session Co-Conveners/Chairs:* **Klaus Gessner** and **Chris Kirkland** - T21F: Characterizing Cratons and Craton Margins II *Session Primary-Convener:* **Huaiyu Yuan** - T22A: Characterizing Cratons and Craton Margins III *Session Co-Conveners/Chairs:* **Klaus Gessner** and **Chris Kirkland** - T22A: Characterizing Cratons and Craton Margins III *Session Primary Convener/Co-Chair:* **Zheng Xiang Li** - T21G: How Earth Works 100 Years after Wegener's Continental Drift Theory: Supercontinent Cycles, Plate Tectonics, and Global Geodynamics II

Greenland Day Conference, Perth, Australia, 9 December 2015	*Conference Organiser:* **Marco Fiorentini**

SELECTED WORKSHOP ROLES

Activity	Details & Participant/s	Date
CET Seminar Series	**Cam McCuaig**	2015
CCFS/EPS Seminar Series	**CCFS/EPS MQ**, organised by Stefan Loehr	2015
Pure Gold - Orogenic gold workshop, Red Lake	Developed and presented by **Cam McCuaig**	March 2015
First ACTER (Australia-China Joint Research Centre for Tectonics and Earth Resources (http://tectonics.curtin.edu.au) annual field workshop - Tectonic History of the South China Block and Approaches for Tectonic Analysis. See workshop report and photos at http://tectonics.curtin.edu.au/events/workshop-153.cfm Organised by **Zheng-Xiang Li** *(photo Zheng-Xiang Li)* 2-11 March 2015		
EPS HDR Conference Day	Organised by the MQ Department of EPS featuring presentations and posters from EPS and **CCFS MQ PhD students**	11 June 2015
Field trip to NSW south coast for IODP Forum, Canberra	Co-convenor - **Kelsie Dadd**	6-7 July 2015
***"Grand Tour"* astrobiology fieldtrip**	Co-leader - **Martin Van Kranendonk**	16-25 July 2015
2nd Mars 2020 Landing Site Workshop, Monrovia, California	Invited participant - **Martin Van Kranendonk**	4-6 August 2015
Pre Conference Workshop: **The LA-ICP-MS U-(Th-)Pb Network**	Co-organised by **Norman Pearson**	15-16 August 2015
SGA 2015, Nancy (France), **Pre Conference Workshop 7**: Latest advances in the understanding of the genesis of Ni-Cu-PGE mineral systems and associated review on exploration targeting	Co-organised by **Marco Fiorentini**	23 August 2015

SELECTED WORKSHOP ROLES *cont...*

Activity	Details & Participant/s	Date
CCFS Centre-wide Research Meeting	Organised by **CCFS**, Hosted at Macquarie University (see *pp. 4-5*)	21-23 October 2015
Anglogold orogenic gold targeting (Perth)	Lead course developer and presenter, **Cam McCuaig**	November 2015
EPS HDR Conference Day	Organised by the MQ Department of EPS featuring presentations and posters from EPS and **CCFS MQ PhD students**	11 November 2015
CCFS Second Lithosphere Dynamics Workshop, Perth, Sessions: Imaging the architecture and composition of the deep lithosphere - how are we advancing?	Co-organised by **Marco Fiorentini** and **Weronika Gorczyk**, Hosted by UWA	19-20 November 2015
2015 Planetary Research Workshop	**Craig O'Neill** Organised the 2015 Planetary Research Workshop at Macquarie University	26-27 November 2015
CET Members Day	Host, opening Keynote - **Cam McCuaig**	9 December 2015
First **IGCP 648 field workshop** on Supercontinent Cycles and Global Geodynamics, Kailua-Kona, Hawaii	Co-organised by **Zheng-Xiang Li, Weihua Yao** and **Sergei Pisarevsky**	9-12 December 2015

ESTEEM

AWARDS

Participant	Activity
Olivier Alard	Awarded an ARC Future Fellowship
Elena Belousova Selected to receive the 2016 Nancy Millis Award (Medal to be presented formally in May 2016)	
Stephen Foley	2015 Highly Commended for the Jim Piper Award for Excellence in Research Leadership

Participant	Activity
Bill Griffin	Recognised by Thomson-Reuters as a Highly-Cited Researcher (http://highlycited.com)
Received the Royal Society of New South Wales Clarke Medal from Dame Marie Bashir (Patron)	
Zheng Xiang Li	John Curtin Distinguished Professor title by Curtin University, 2015 ARC Australian Laureate Fellowship, 2015 Thomson Reuters Highly Cited Researcher 2014 & 2015 (http://highlycited.com) Curtin University PVC Lifetime Achievement Award, 2015
Robert Loucks	Stillwell Medal of the Geological Society of Australia, awarded to Robert Loucks, for his presentation at the Annual Meeting in Adelaide, June 2015
Laure Martin	UWA Fay-Gale Fellowship
Sue O'Reilly	Recognised by Thomson-Reuters as a Highly-Cited Researcher (http://highlycited.com)
Sue O'Reilly, BIll Griffin, Zheng Xiang Li and Simon Wilde Thomson-Reuters Citation Award for outstanding work on the "*Tectonic Setting of the North and South China Cratons*", ceremony held at the University of Melbourne on 23 June 2015 (http://ip-science.thomsonreuters.com.au/m/pdf/PR_CIA_2015.pdf)	
Simon Wilde	Recognised by Thomson-Reuters as a Highly-Cited Researcher (http://highlycited.com)
Yingjie Yang Awarded 2015 Anton Hales Medal for Research in Earth Sciences Yingjie delivered an award lecture *"The sound of the sea: 3D imaging of the Earth using noise from ocean waves."* (photo right)	 

2015 NEW APPOINTMENTS AND POSITIONS

Kelsie Dadd	Membership on ANZIC (IODP) Governing Council
Ian Fitzsimons	Fellow of the Geological Society, London Fellow of the Mineralogical Society Keynote Speaker for SEG 2016: Tethyan Tectonics and Metallogeny
Marco Fiorentini	Appointed Associate Editor Mineralium Deposita
Weronika Gorczyk	Appointed as committee member of Geoconferences WA
Bill Griffin	Co-Convenor for Session 09a Sustainable Resourcing of Ore Deposits Related to Ultramafic-Mafic Magmas at Goldschmidt 2016 at Yokohama, Japan
Yongjun Lu	Appointed Associate Editor for SEG 2016 Special Publication on Tethys Appointed Councillor for Society for Geology Applied to Mineral Deposits (SGA) in 2016-2019
Craig O'Neill	Member of the Australian Academy of Science National Committee for Earth Sciences
Sue O'Reilly	Member, 2015 ERA Research Evaluation Committee Member Executive Committee, UNCOVER national initiative (Auspices of the Australian Academy of Sciences) Chair, Academy of Sciences National Committee for Earth Sciences, and Decadal Plan preparation Elected Member of Council, Australian Academy of Sciences (http://www.mq.edu.au/newsroom/2014/11/14/eminent-geologist-joins-australian-academy-of-science-council/) Appointed Convenor - Lithosphere-Asthenosphere boundary session, IGC 2016

EDITORIAL APPOINTMENTS	
Acta Geologica Sinica	**Li**
Acta Geoscientia Sinica	**Li**
American Journal of Science	**Wilde**
American Mineralogist	**Piazolo**
Chemical Geology	**Wilde**
Cogent Geosciences	**O'Neill, Moresi**
EGU Journal Solid Earth	**Afonso, Schaefer**
Exploration Geophysics	**Yang**
Geobiology	**Wacey**
Geodynamics & Tectonophysics	**Pisarevsky**
Geology	**C. Clark**
Geological Society of America Bulletin	**Griffin, Li**
Geosphere	**Yuan**
GeoResJ	**George, Jacob, Schaefer**
Journal of the Geological Society, London	**C. Clark, Fitzsimons**
Journal of Jilin University - Earth Science	**Wilde**

EDITORIAL APPOINTMENTS *cont...*	
Journal of Metamorphic Geology	**Brown**
Journal of Petrology	**Turner**
Journal of Structural Geology	**Piazolo**
Lithos	**C. Clark, Foley, Griffin**
Mineralium Deposita	**Fiorentini**
Nature Scientific Reports	**Wacey**
Ore Geology Reviews	**Bagas**
Physics and Chemistry of Minerals	**McCammon**
Precambrian Research	**Barley, Pisarevsky, Van Kranendonk**
Scientific Reports	**Piazolo**

OUTREACH

Forum	Participant/s	Date
University of Hong Kong - Public lecture on 4D isotopic mapping of the lithosphere	**Marco Fiorentini**	30 January 2015
Judge at **FIRST Robotics Competition**	**Kelsie Dadd**	13-14 March 2015
Trial voyage of MNF RV Investigator from Hobart - Participant	**Kelsie Dadd**	30 April – 5 May 2015
Helmholtz Centre for Environmental Research, Leipzig, Germany - Public lecture	**Matt Kilburn**	6 May 2015
2015 Australian Academy of Science - Science at the Shine Dome - 2015 Anton Hales Medal award presentation entitled *"The sound of the sea: 3D imaging of the Earth using noise from ocean waves"*	**Yingjie Yang**	27 May 2015
Royal Society of New South Wales – W.B. Clarke Memorial Lecture held at Macquarie University	**Bill Griffin**	6 August 2015
Judge at **Tempe High School** Year 9 Annual Science Fair	**Kelsie Dadd**	20 August 2015
Year 10 Careers Fair, **Tempe High School**	**Kelsie Dadd**	20 August 2015
ANU RSES - Guest Speaker on *"Onset of subduction and the genesis of TTG's (tonalites-trondhjemites-granodiorites) in the earliest Earth"*	**Tracy Rushmer**	27 August 2015
Herbert-Smith-Freehills Law Firm - Lecture/lunch to discuss sulfur isotopes as key to exploration targeting	**Crystal LaFlamme**	October 2015
LEAP University Experience Day, Macquarie University - This event is held as part of the LEAP Macquarie Mentoring program. The aim of the day is to bring high school students from refugee backgrounds onto campus to expose them to university life and to demystify the concept of university for them.	**Kelsie Dadd**	16 October 2015
Talk on volcanoes at **SDN Northern Suburbs Children's Education and Care Centre**	**Kelsie Dadd**	4 November 2015
Geological Survey of Denmark and Greenland - Public lecture on magma emplacement dynamics	**Marco Fiorentini**	16 December 2015

MEDIA

Activity	Participant/s	Date, Forum	Web address
Distinguished Professor William Griffin	**Bill Griffin**	23/03/2015, MQ Research impact	http://www.mq.edu.au/research-impact/2015/03/23/distinguished-professor-william-griffin/#.VsqOspN97OZ
Distinguished Professor Sue O'Reilly	**Sue O'Reilly**	23/03/2015, MQ Research impact	http://www.mq.edu.au/research-impact/2015/03/23/distinguished-professor-sue-oreilly/#.VsqPRZN97OY
Continental crust beneath Southeast Iceland	Co-Author: **Bill Griffin**	30/03/2015, ABC nyheter, 30.3.2015	Radio Interview
Scientists believe sunken continent is under Iceland	Co-Author: **Bill Griffin**	30/03/2015, Dagbladet nett	http://m.db.no/2015/03/30/nyheter/forskning/utenriks/island/38482749/
Sunken continent under the southeast coast of Iceland	Co-Author: **Bill Griffin**	30/03/2015, Forskning.no	http://forskning.no/2015/03/sunket-kontinent
Fragment of Jan Mayen Microcontinent discovered beneath Iceland points to *'lost'* continents	Co-Author: **Bill Griffin**	30/03/2015, International Business Times	http://www.ibtimes.co.uk/fragment-jan-mayen-microcontinent-discovered-beneath-iceland-points-lost-continents-1494187
Deeply buried continental crust under Iceland	Co-Author: **Bill Griffin**	31/03/2015, ScienceNordic	http://sciencenordic.com/content/deeply-buried-continental-crust-under-iceland
Scientific study shines new study on the origin of diamonds	**Marco Fiorentini**, **Andrea Giuliani**	20/04/15, UWA News	http://www.news.uwa.edu.au/201504207493/research/scientific-study-shines-new-light-source-diamonds
Genetic link between MARID mantle and diamond bearing orangeites	**Marco Fiorentini**	20/04/15, Singapore Radio, Radio News 938LIVE	Radio Interview
Genetic link between MARID mantle and diamond bearing orangeites	**Marco Fiorentini**	21/04/15, ABC Sunshine Coast, 90.3LIVE	Radio Interview
Diamond study reveals key information about the earth	**Marco Fiorentini**, **Andrea Giuliani**	21/04/15, Mining.com	http://www.mining.com/diamond-study-reveals-key-information-about-the-earth/?utm_source=digest-en-mining-150420&utm_medium=email&utm_campaign=digest
Changing the picture of Earth's earliest fossils (3.5-1.9 Ga) with new approaches and new discoveries	Co-Author: **David Wacey**	April 2015, ABC North West morning show & ABC Bunbury drive time	Radio Interviews
Oldest evidence of life on Earth is WRONG: 3.46 billion-year-old *'fossils'* were simply stacks of clay minerals	Co-Author: **David Wacey**	22/4/2015, Daily Mail Australia	http://www.dailymail.co.uk/sciencetech/article-3049223/Oldest-evidence-life-Earth-WRONG-3-46-billion-year-old-fossils-simply-stacks-clay-minerals.html
A 3.5-billion year old Pilbara find is not the oldest fossil: so what is it?	Co-Author: **David Wacey**	22/4/2015, The Conversation	http://theconversation.com/a-3-5-billion-year-old-pilbara-find-is-not-the-oldest-fossil-so-what-is-it-40482
Diamond discovery kick	**Marco Fiorentini**, **Andrea Giuliani**	23/04/2015, Mining Monthly	http://miningmonthly.com/equipment/exploration/diamond-discovery-kick/
New Earth dawns: supercontinent slowly takes shape	**Zheng Xiang Li**	26/4/2015, Canberra Times	http://www.canberratimes.com.au/national/education/new-earth-dawns-supercontinent-slowly-takes-shape-20150426-1mqa1q
New Earth dawns: supercontinent slowly takes shape	**Zheng Xiang Li**	26/4/2015, Sydney Morning Herald	http://www.theage.com.au/national/education/new-earth-dawns-supercontinent-slowly-takes-shape-20150426-1mqa1q.html
Earth's newest supercontinent is taking shape: Land masses are already drifting together to form *"Amasia"*	**Zheng Xiang Li**	28/4/2015, Daily Mail Australia	http://www.dailymail.co.uk/sciencetech/article-3059002/Earth-s-newest-supercontinent-taking-shape-Land-masses-drifting-form-Amasia.html
Australia on path to join supercontinent *"Amasia"*	**Zheng Xiang Li**	28/4/2015, Science Network WA report	http://www.sciencewa.net.au/topics/environment-a-conservation/item/3494-australia-on-path-to-join-supercontinent-amasia - k2Container)

Activity	Participant/s	Date, Forum	Web address
Could Earth host another supercontinent?	**Zheng Xiang Li**	28/4/2015, UPI Science News	http://www.upi.com/Science_News/2015/04/28/Could-Earth-host-another-supercontinent/2341430226932/
Australia on path to join UK as part of supercontinent *"Amasia"*	**Zheng Xiang Li**	03/5/2015, news .com.au	http://www.news.com.au/technology/science/evolution/australia-on-path-to-join-uk-as-part-of-supercontinent-amasia/news-story/9e009af59b45b6853c687a5e1eab7c33
Scientific study shines new light on the origin of diamonds	**Marco Fiorentini**, **Andrea Giuliani**	12/05/15, Geology Page	http://www.geologypage.com/2015/04/scientific-study-shines-new-light-on.html
Trialling the new Marine National Facility	**Kelsie Dadd**	12/05/2015, MQ Research impact	http://www.mq.edu.au/research-impact/2015/05/12/trialling-the-new-marine-national-facility/#.VsqPzZN97OY
Big History Spotlight - Juan Carlos Afonso	**Juan Carlos Afonso**	14/05/15, Big History Institute, MQ	http://bighistoryinstitute.org/research/centres_and_groups/big_history_institute/thresholdnine/issue_three/spotlight_juan_carlos
3.46-billion-year-old '*fossils*' were not created by life forms	Co-Author: **David Wacey**	20/5/2015, Science magazine website	http://news.sciencemag.org/earth/2015/04/3-46-billion-year-old-fossils-were-not-created-life-forms
The most ancient evidence of life on Earth?	Co-Author: **David Wacey**	25/5/2015, Cosmos magazine	https://cosmosmagazine.com/life-sciences/most-ancient-evidence-life-earth
Large igneous provinces associated with mid-ocean ridges	Co-Author: **Juan Carlos Afonso**	28/5/2015, Phys.org	http://phys.org/news/2015-05-large-igneous-provinces-mid-ocean-ridges.html
World-class geoscientist awarded $2.9m Australian Laureate Fellowship	**Zheng Xiang Li**	June, Curtin University News	http://news.curtin.edu.au/media-releases/world-class-geoscientist-awarded-2-9m-australian-laureate-fellowship/
Filming related to World's Oldest Crystals at Jack Hills "Between Heaven and Earth", producer: Arte France, Host: Serge Brunier. Episode: "Australia, History of Life on Earth"	**Simon Wilde**	30/01/2015-1/02/2015, Filming in Murchison 01/06/2015, Aired in France	http://www.pointdujour-international.com
Supercontinent revolution	**Zheng Xiang Li**	12/6/2015, Science Meets Business	http://sciencemeetsbusiness.com.au/supercontinent-revolution/
Continents collide	**Simon Wilde**	12/6/2015, Science Meets Business	http://sciencemeetsbusiness.com.au/continents-collide/
Citation & Innovation Awards 2015	**Sue O'Reilly**, **Bill Griffin**, **Simon Wilde**, **Zheng-Xiang Li**	23/6/2015, IP & Science - Australia-New Zealand	http://ip-science.thomsonreuters.com.au/citation_innovation_awards_2015/
Curtin researchers WA's only winners at prestigious awards	**Simon Wilde**, **Zheng-Xiang Li**	23/6/2015, Curtin Media Release	http://news.curtin.edu.au/media-releases/curtin-researchers-was-only-winners-at-prestigious-awards/
Curtin researchers WA's only winners at prestigious awards	**Simon Wilde**, **Zheng-Xiang Li**	23/6/2015, Curtin's Vice-Chancellor Blog	http://blogs.curtin.edu.au/vice-chancellor/note-to-staff/2015/23-june-2015/
Macquarie University academics honoured at Thomson Reuters Australian Citation & Innovation Awards	**Sue O'Reilly**, **Bill Griffin**	24/6/2016, MQ Newsroom	http://mq.edu.au/newsroom/2015/06/24/macquarie-university-academics-honoured-at-thomson-reuters-australian-citation-innovation-awards/
Our fine three	**Sue O'Reilly**, **Bill Griffin**	28/6/2015, This Week, MQ	http://www.mq.edu.au/thisweek/archives/2015/06/our-fine-three/#.VxxLXJN97OY
The source of diamonds	**Marco Fiorentini**	6/08/15, Radio New Zealand National	Radio Interview
Volcanic history dredged from deep-sea rocks	**Kelsie Dadd**	28/8/2015, ScienceNewsWA	http://www.sciencewa.net.au/topics/environment-a-conservation/item/3746-volcanic-history-dredged-from-deep-sea-rocks

MEDIA *cont...*

Activity	Participant/s	Date, Forum	Web address
The multiple sulfur isotope project	**Crystal LaFlamme**, **Stefano Caruso**, **Cam McCuaig**, **Marco Fiorentini**	07/09/2015, ABC News	http://www.abc.net.au/news/2015-09-07/sulphur-could-hold-key-to-next-generation-of-mining-deposits/6756602
New research reveals Tasmania was once far from mainland Australia	**Nathan Daczko**	07/09/2015, UTAS Communications & Media	http://www.media.utas.edu.au/general-news/all-news/new-research-reveals-tasmania-was-once-far-from-mainland-australia
Sulphur could hold key to next generation of mining deposits, research suggests	**Stefano Caruso**	07/9/2015, National news broadcast	Short video
Jigsaw puzzles in WA holds the keys to understanding the birth of our continent	**Huaiyu Yuan**	09/9/2015, MQ Newsroom	http://www.mq.edu.au/newsroom/2015/09/09/jigsaw-puzzles-in-wa-hold-the-keys-to-understanding-the-birth-of-our-continent/
Helping choose the Mars 2020 rover landing site	**Martin Van Kranendonk**	10/09/2015, UNSW Newsroom	http://newsroom.unsw.edu.au/news/science-tech/helping-choose-mars-2020-rover-landing-site
Sulfur holds key to next generation of mining deposits	**Crystal LaFlamme**, **Stefano Caruso**	10/9/2015, ABC Evening News	http://www.cet.edu.au/commodity-topics/porphry-systems/2015/09/10/cet-featured-in-abc-evening-news-sulfur-holds-key-to-next-generation-of-mining-deposits
Ancient minerals on Earth can help explain the early solar system	**Steve Reddy**	28/09/2015, The Conversation	https://theconversation.com/ancient-minerals-on-earth-can-help-explain-the-early-solar-system-46991
Deciphering the Earth's history through passive seismic noise	**Chengxin Jiang**	12/10/2015, MQ Research impact	http://www.mq.edu.au/research-impact/2015/10/12/deciphering-the-earths-history-through-passive-seismic-noise/#.VsqPlZN97OY
Time Machine - Scientists have used groundbreaking technology to figure out how the Earth looked a billion years ago	**Zheng Xiang Li**	31/12/2015, Quartz	http://qz.com/577842/scientists-have-used-groundbreaking-technology-to-figure-out-how-the-earth-looked-a-billion-years-ago/

VISITORS

CCFS fosters links nationally and internationally through visits of collaborators to undertake defined short-term projects, or short-term visits to give lectures and seminar sessions. Formal collaborative arrangements are facilitated by partnerships in grants with reciprocal funding from international collaborators.

All Australian and international visitors are listed in *Appendix 7*.

They have participated in collaborative research, technology exchange, seminars, discussions and joint publications and collaboration in postgraduate programs.

CCFS provides funds to intetnational visitors who will add value to CCFS programs and contribute to the high visibility of research in the Centre.

Recipients of 2015 CCFS Visiting Researcher Funds:

Dr Bjarne Almqvist, Department of Earth Sciences (Geophysics), Uppsala University, Sweden

Associate Professor David Baratoux, Géosciences Environnement, University of Toulouse, France

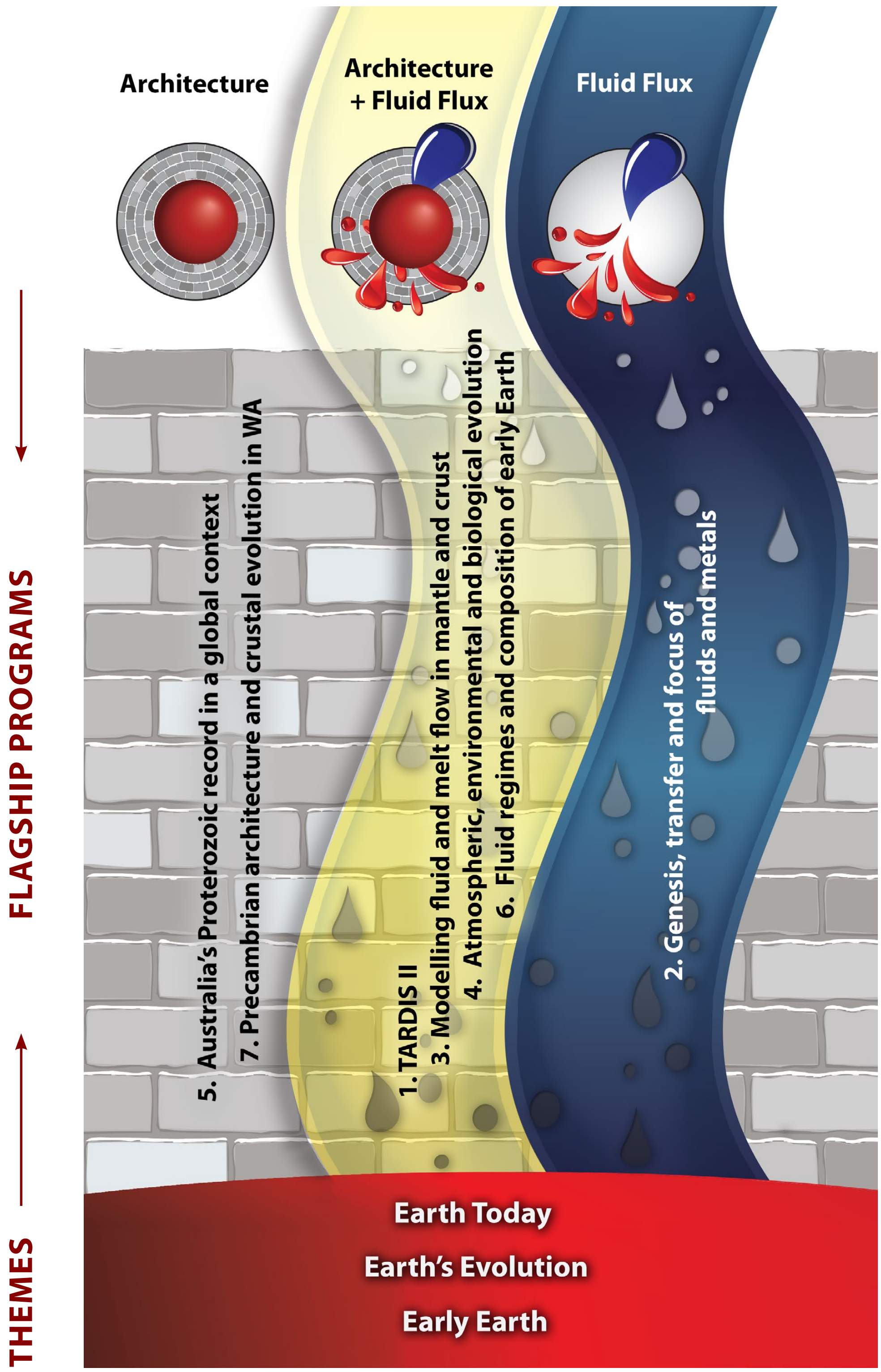
Professor Pedro Díez, Universitat Politècnica de Catalunya, Barcelona, Spain

Professor Nikolay Kuznetsov, Geological Institute, Russian Academy of Science, Moscow, Russia

CCFS sponsored visitor Professor Nikolay Kuznetsov and Professor Nadezhda Krivolutskaya working in the GAU on zircons from the Norilsk intrusions.

Research highlights 2015

Following the conceptual framework outlined on *page 6*, these Research highlights are identified as contributing to understanding Earth Architecture (the '*roadmap*' for fluids) and/or Fluid Fluxes (the '*traffic report*'), with logos for easy attribution.
For a full description of the Flagship Programs, see *Appendix 1*.



COPA: the Capricorn Orogen Passive-source Array

The SIEF Project

In 2013, a major Science and Industry Endowment Fund (SIEF) project, the "*UNCOVER Australia: Capricorn Distal Footprints Project*" was awarded to CSIRO, UWA, Curtin and GSWA. The SIEF project is one of the largest multi-method surveys attempted in Australia and aims to image the lithosphere from very shallow to its deeper levels. The project builds on current knowledge to deliver improved understanding of the evolution and controls on mineral systems in the Capricorn. The end goal is to apply these generic learnings elsewhere in order to develop a set of integrated large-scale geological and geophysical datasets that can assist in constraining whole lithosphere architecture and tectonic evolution and boost exploration discovery success in covered terrains in Australia

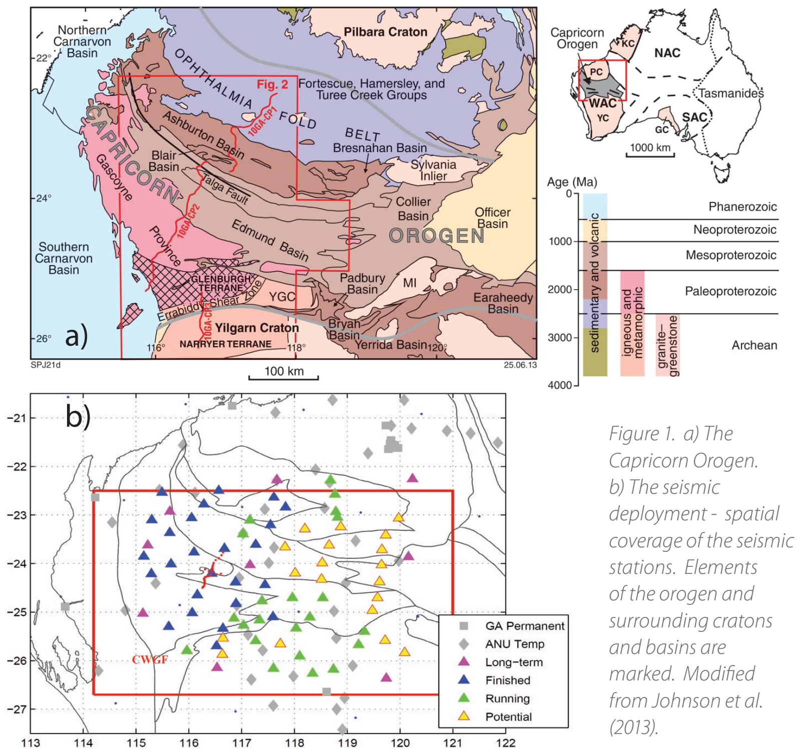


Figure 1. a) The Capricorn Orogen. b) The seismic deployment - spatial coverage of the seismic stations. Elements of the orogen and surrounding cratons and basins are marked. Modified from Johnson et al. (2013).

The Capricorn Orogen

The Capricorn Orogen of Western Australia is a 1000 km long, 500 km wide region of variably deformed rocks located between the Pilbara and Yilgarn Cratons (Fig. 1a, right). It records the Paleoproterozoic assembly of these cratons to form the West Australian Craton, and over one billion years of intracratonic reworking that followed. Owing to this reworking, the location of major crustal structures and the broad architecture of the orogen are poorly constrained. To improve the exploration potential of the region, a better understanding of the crustal architecture across the orogen is critical, especially identification the location and orientation of major crustal structures and craton edges, as well as any island arcs, or exotic accreted crustal material (*Johnson et al., Australian Journal of Earth Sciences, 2013*; Fig. 1a).

The COPA Deployment

The overall goal is to integrate other geological and geophysical datasets and produce 3D multiple-scale seismic images across the orogen. This will provide direct constraints on local geological models for the timing and kinematic evolution of faults and shear zones in the region and its 4D metallogenic history. We will also provide new insights on the tectonic amalgamation of the Western Australian craton. The main tools of the project are seismic tomography (body waves and surface wave/ambient noise) and receiver function CCP imaging. These two commonly used earthquake-seismology methods best fit the 2D design of the passive source project.

With a careful design of a 2D array that takes advantage of previous passive-source studies in the region, the proposed long-term and short-term deployments give us a 2D grid that spans a nearly 500 km by 500 km surface area. Station spacing is roughly 40 km and the 36 months in total deployment will guarantee enough data recording for 3D structure imaging using body wave tomography, ambient noise surface wave tomography and P- and S-wave receiver function Common Conversion Point (CCP) stacking techniques. 34 sets of seismometers loaned from the ANSIR national instrument pool (with 2 as backup) have been deployed in the western half of the orogen since March 2014. In October 2014 a 25-site High-resolution Passive Source (HPS) array was also deployed, with varying 2, 4, and 8 km station spacing to focus on shallow crustal structure across the Collier Basin, Edmund Basin and the Gascoyne Province. The HPS array was deployed in October 2015.

Preliminary Results: Bulk Crustal Structure

In the passive-source studies, we will test several hypotheses that 1) distinct crustal blocks are seen continuously throughout the orogen (using ambient noise/body wave tomography); 2) distinct lithologies are present in the crust and upper mantle across the orogen (using receiver function CCP images); and 3) crustal and lithosphere deformation along craton margins in general follows '*wedge*' tectonics (e.g. subduction of juvenile blocks under the craton mantle, on craton-ward dipping sutures; *Snyder, Tectonophysics, 355, 7-22, 2002*).

Preliminary results of the crustal structure in the orogen are available from seismic receiver functions. A simple H-k stacking technique (*CCFS publication #649; Research highlight pp. 64-65*) stacks available receiver functions to obtain an optimum pair of bulk crustal thickness (H) and Vp/Vs ratio (k; equivalent to

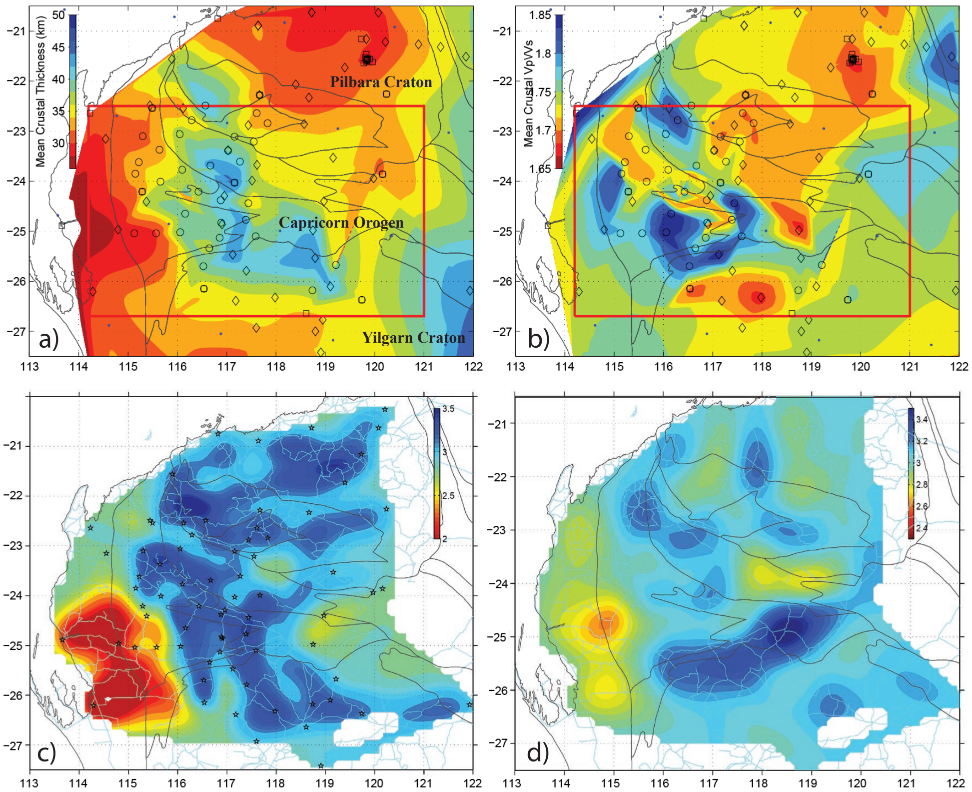


Figure 2. Preliminary results from the COPA deployment. a) and b), mean crustal thickness (in km) and Vp/Vs ratio. c) and d), shear wave velocity maps from ambient noise showing peak period at 2.5 s and 15 s, corresponding to maximum sensitivity at 3 and 20 km, respectively.

Poisson's ratio; an indicator of crustal rock composition). The maps show bulk crustal thickness, Vp/Vs ratio, bulk crustal Vp velocity and the crustal density anomaly from gravity inversions. The western Capricorn Orogen is thicker, denser and higher-velocity, compared to the two cratons. Compositionally the western orogen is complex - it may indicate that different terranes of deformation processes were involved during the amalgamation of the WA craton in the Proterozoic. The northern margin of the Yilgarn Craton shows anomalously thicker, denser and higher velocity crust, and abrupt changes in the crustal conductivity are also observed in the MT study.

A tomographic inversion using ambient noise is currently being conducted to obtain shear wave velocities in a 3D volume of the orogenic crust. Available data for all possible station pairs are cross-correlated and stacked to obtain the empirical surface wave traveling between the station pair. Phase and group velocities can be measured for each station pair, which forms a path in a tomographic problem. Figure 2 shows the group velocity tomographic results at period 2.5 s (~3 km peak depth); and period 15 s (mid-crust). Significant structural differences are evident in the shallow and mid-crust. The high-velocity northern margin of the Yilgarn Craton is prominent, as seen previously in the receiver functions and MT images. The 3D tomographic model of shear velocity is under construction. More data are expected from the deployment to push the imaging capability to the lower crust, and to extend the horizontal coverage in the eastern Capricorn Orogen by April 2017.

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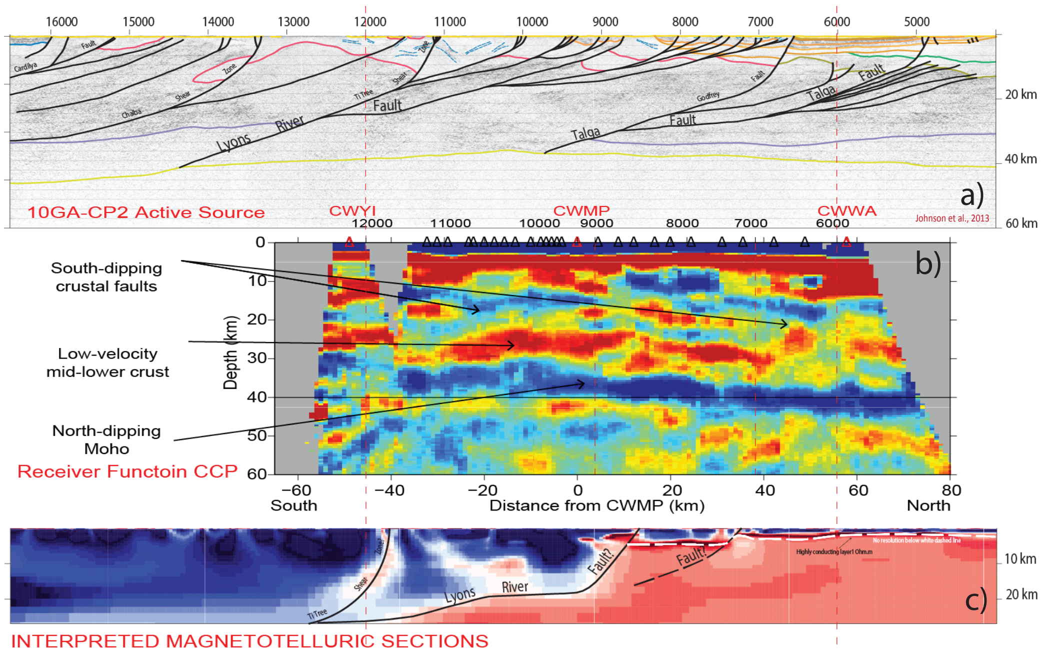

Figure 3. Comparison of the crustal scale results along the high resolution line from the active source (a; Johnson et al., 2013), the passive source CCP stack (b; this study); and the MT (c; Heinson et al., 2012). Note the prominent Moho interface, the truncations of crustal discontinuities, and the low-velocity mid- to lower crust inferred from the negative velocity contrast.

Preliminary Results: A High Resolution Crustal Cross-section
A receiver function CCP (common-conversion-point) stack is applied to the high resolution line (HPS) to reveal crustal discontinuities. The results show good correlation with the active source and magnetotelluric studies (*Johnson et al. 2013; Heinson et al., GSWA Report 2012*). The passive source CCP image shows comparable crustal structures: north-dipping Moho; and south-dipping crustal faults (truncated crustal discontinuities). A slow-velocity mid- to lower crust is inferred from the negative velocity gradients in the centre of the array, consistent with the ambient noise observations, and the highly conductive mid-crust in the MT image.

This project is part of CCFS Theme 3, Earth Today, and contributes to understanding Earth's Architecture.

Contact: Huaiyu Yuan
Funded by: CCFS Flagship Program 7, SIEF

The sulfur cycle in the Palaeoproterozoic Earth

The Earth's crust is a complex and dynamically evolving chemical interface between two convective fluid systems: the endosphere (linked core and mantle) and the exosphere (linked hydrosphere and atmosphere). The nature of the physical and chemical processes that occur on the surface of the planet are intimately linked by the energy available from the sharp chemical and thermal gradients that exist across this interface. On modern Earth, island/volcanic arcs are the direct consequence of subduction processes that occur at convergent plate boundaries, and are the factories where juvenile continental crust is formed and where explosive volcanic eruptions emit large quantities of gases into the atmosphere. There remains considerable uncertainty with respect to the key processes that occurred during the transition from the Archaean to the modern Earth. One of the key questions is whether ancient arcs behaved similarly to modern ones. The fragmented geological record of the Palaeoproterozoic (2.5-1.6 billion years ago) and Archaean (>2.5 billion years ago) eons makes it difficult to answer these questions with any certainty, allowing for a proliferation of inferences and unanswered questions.

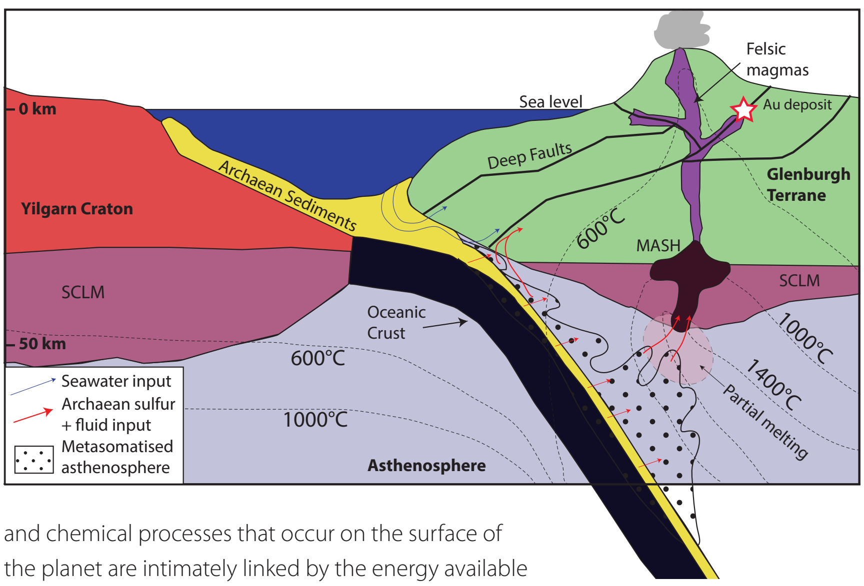

Figure 1. Schematic section through the Glenburgh continental arc system at ca 2.0 Ga, prior to collision between the Archean Glenburgh Terrane and Yilgarn Craton. This diagram highlights the development of a MASH (Melting, Assimilation, Storage, Homogenisation) zone where mafic magmas generated from partial melting of the metasomatised asthenosphere and subcontinental lithospheric mantle (SCLM) pool at their level of neutral buoyancy and differentiate into more buoyant felsic melts, which then ascend through the crust along major fault zones to produce the felsic magmatism, i.e. the Dalgaringa Supersuite, observed in the Glenburgh Terrane. Archaean sulfur and gold bearing fluids would also travel up these deep faults where they may interact with seawater, generating the observed sulfur isotope 'mixing line'.

A key insight into this knowledge gap comes from better understanding the shift in the isotopic signature of sulfur through time. Sulfur is a key volatile element that is cycled between the different crustal and mantle reservoirs during arc magmatism, and thus may be used as a tracer. However, the cycle of sulfur between the inner parts of our planet and the atmosphere in the Palaeoproterozoic remains poorly constrained. As a result, our understanding of the development of early life and many other earth processes in which sulfur plays a key role, including climate change, biological evolution and ore deposit genesis, have been hindered. We need isotopic markers that can trace the sources and map the path of this element through the uppermost layers of the upper mantle and crust (the lithosphere).

The discovery of the presence of anomalous mass-independent fractionation of sulfur (MIF-S) signatures in Archaean sedimentary rocks provides a revolutionary way to probe the global sulfur cycle. These anomalies occur because in the ancient atmosphere, which lacked ozone, cosmic radiation could produce isotopes (such as ^{33}S) that are not formed now. This study focuses on the Palaeoproterozoic Glenburgh sulfur-bearing gold deposit, which is a natural laboratory ca 2 billion years old, hosted in the Glenburgh arc of Western Australia. Because this arc developed at the margin of a subducting Archaean block, we applied multiple sulfur isotope analysis as a chemically conservative tracer to test whether Archaean MIF-S sulfur could be detected. Results show that Archaean sulfur can be traced throughout the Palaeoproterozoic Glenburgh arc (Fig. 1).

This is an extraordinary discovery as it provides key constraints on the sources of volatiles and metals in arc environments. This is still a heavily debated topic, as there is a mass-balance problem between the known concentrations of these elements in the mantle wedge below arc systems and the observed concentrations in arc magmas and associated mineralisation. Some workers have suggested that, particularly in the case of gold deposits formed in continental arcs, the ultimate source of gold is from subducted carbon-rich sedimentary rocks attached to the downgoing slab. In fact, since gold is insoluble in H_2O, it is thought that it may be mobilised in the form of Au sulfide complexes in fluids at high temperatures and pressures, such as those found in arc magmatic environments. Therefore, the isotopic composition of sulfide should also reflect a similar source, as is demonstrated in the dataset presented in this study.

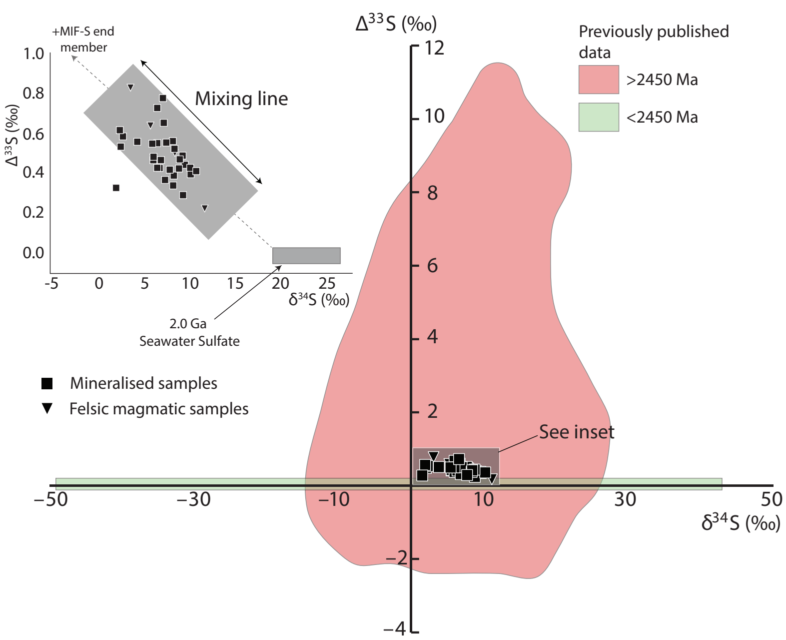

Figure 2. Δ³³S versus δ³⁴S from Glenburgh (this study) compared to previously published S-isotope data. Points shown have error bars smaller than the size of the points in all cases.

The application of spatio-temporally constrained chemically conservative isotopic tracers such as MIF-S is critical for a better understanding of tectonic processes that drive fluid and metal transfer from Archaean cratons into their reworked margins and the operation of arc magmatism. At the Glenburgh deposit, mixing between sulfur isotope end-members (Paleoproterozoic seawater-derived sulfate and Archaean shale-derived pyrite; Fig. 2) is, in effect, recording the progressive closing of an ocean and a tectonic switch from subduction of oceanic crust to the onset of continent-continent collision with the Yilgarn Craton. Hence, multiple sulfur isotope data are able to image a process that is cryptic in most other currently available datasets, showing that sulfur cycling in arc settings occurs on very large scales, from the atmosphere-hydrosphere through to the lithosphere during crustal generation. If this happened in the Archean, it presumably could have happened throughout geological history, although we have no equivalent tracers for post-Archean processes.

This project is part of CCFS themes 2 and 3, Earth's Evolution and Earth Today, and contributes to understanding Earth's Architecture and Fluid Fluxes.

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Funded by: MRIWA Distal Footprint Capricorn Study, umbrella of - but not funded by - CCFS Flagship Program 4

Primitive pyroxenites delaminated from ancient island arc

One of the major debates of modern petrology, known as the continental crust paradox, arises essentially from the discrepancy between the net basaltic output of modern arc magmatism and the average andesitic composition of the continental crust. If any post-Archean continental crust was to be made by arc magmatism, this paradox needs to be resolved. Among the potential explanations is that the mafic-ultramafic counterpart of the differentiated felsic crust had to be removed. After being postulated theoretically, and explained numerically and experimentally, the delamination (i.e. convective removal) of dense arc cumulates has been seismically evidenced. However, field evidence for this key geological process has been hard to find.

In north-western Spain, the Herbeira massif of the Variscan Cabo Ortegal Complex hosts one of Earth's rare exposures of sub-island-arc mantle. New field and petrographic investigations of this 600 m-thick mafic-ultramafic section have defined a crystallisation sequence of primitive cumulates (dunites ± chromitites, wehrlites and olivine websterites). Their particularly high CaO/Al_2O_3 (2.2-11.3), high concentrations of compatible elements and a signature of high large ion lithophile elements (LILE) / high field strength elements (HFSE) implies a origin from unusual arc magmatism. High-Ca parental melts of *cont...*

Figure 1. The Herbeira cliffs (621 m) of northern Galicia, Spain are the highest sea cliffs in continental Europe. They expose the largest mafic-ultramafic section of the Cabo Ortegal Complex, one of the only sub-island-arc mantle exposures in the world.

boninitic to picritic affinities were generated from shallow (<2 GPa) fluid-fluxed melting of a refractory lherzolite, involving carbonatite metasomatism. Following dynamic melt-rock interaction at shallower depths (<1.2 GPa), massive websterites and rare opx-rich websterites were produced. Chromatographic reequilibration accompanied the late magmatic migration of residual melts, which produced a wide range of rare-earth-element (REE) patterns.

Textural observations and preliminary electron back-scattered diffraction (EBSD) data indicate that Cabo Ortegal pyroxenites and their host peridotites record the development of sheath folds and mylonites during high shear-strain deformation, following high-temperature deformation. Peak metamorphism was reached under eclogite-facies conditions (1.6-1.8 GPa and 780-800°C) and exhumation into amphibolite-facies conditions then occurred. This complex tectonothermal record encapsulates delamination, high-pressure metamorphism, and exhumation of the arc root, which resulted from gravitational instabilities and subduction-channel processes.

The Herbeira massif thus may represent the first recognised piece of delaminated arc root, which originated as primitive boninitic to picritic cumulates in a peridotite matrix. It may offer insights into the problem of the '*andesitic*' continental crust.

This project is part of CCFS themes 2 and 3, Earth's Evolution and Earth Today, and contributes to understanding Earth's Architecture and Fluid Fluxes.

Contacts: Romain Tilhac, Hadrien Henry, Sue O'Reilly, Bill Griffin, Norman Pearson, Michel Grégoire, Georges Ceuleneer (Géosciences Environnement Toulouse, GET, France).

Funded by: Flagship Program 1, iMQRES scholarships, EPS postgraduate funds, CNRS funds (M. Grégoire, G. Ceuleneer). Two cotutelle programs between Macquarie and Paul Sabatier University, Toulouse, France have been established for the study of the Cabo Ortegal Complex.

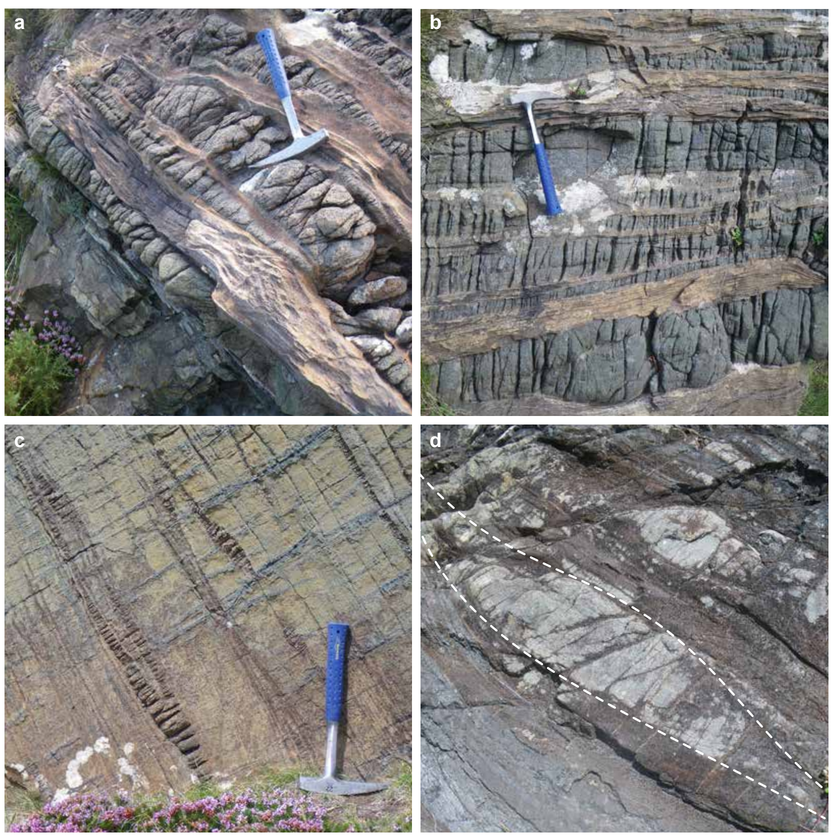
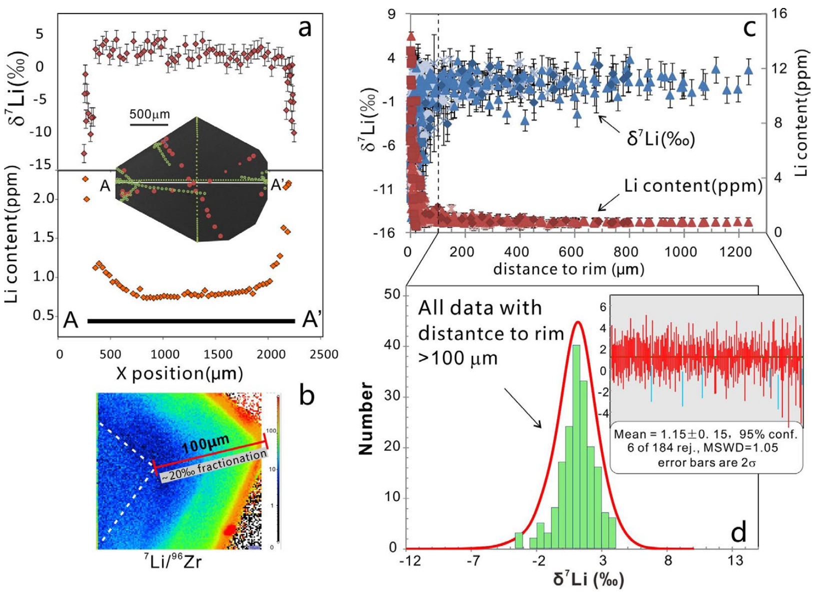


Figure 2. Typical exposures of Cabo Ortegal pyroxenites and dunites (a and b); individual pyroxenite layers may reach up to 3m thickness. Boudinaged pyroxenite layers in harzburgites bear witness to deformation under high-temperature conditions (c). The characteristic sigmoid shape of sheath folds developed from high shear strain of pyroxenites (d) and peridotites during delamination and subduction.

Extreme lithium isotopic fractionation in three zircon standards (Plešovice, Qinghu and Temora)



Li isotopes in zircon are a new isotopic tracer for studying the origin and genesis of granitoid rocks and their implications for the early Earth evolution. However, there is still controversy as to whether Li isotopes in zircon retain their magmatic signatures or are modified by later processes. To understand Li behaviour in zircons, we have analysed Li isotopes and abundance in crystals of three zircon standards (Plešovice, Qinghu and Temora) commonly used for microbeam analysis of U-Pb age and O-Hf isotopes. We have also mapped Li concentration ([Li]) (image: 150 µm × 150 µm) on selected grains, using a Cameca 1280HR Secondary Ion Mass Spectrometer (SIMS). All zircon grains have a rim 5-20 µm wide in which [Li] is 5 to 20 times higher than the in core. Large isotopic fractionations (up to ~20‰) are observed in thin zircon rims (~50 µm) of single grains. The measured δ^7Li values range from -14.3 to +3.7‰ for Plešovice, -22.8 to 1.4‰ for Qinghu and -4.1 to 16.1‰ for the Temora zircon. The [Li] and δ^7Li are highly variable at the rims but relatively homogenous in the cores of the grains. From zircon rim to core, the [Li] decreases rapidly, while the δ^7Li increases, suggesting that the large isotopic variation of Li in zircons could be caused by diffusion. Our data demonstrate that areas with homogeneous δ^7Li in the cores of large zircon grains can retain the pristine isotopic signatures of the magmas, while analysis of bulk-rocks and/or mineral separates might produce false data: values representing mixing of rims and cores.

Figure 1. a) Trace outlines on the CL image of Plešovice-R show the position of the Li isotopic and [Li] measurements by SIMS; b) The ion image of the variation of Li and Y content (bright colours = higher concentration); c) δ^7Li and [Li] vs relative distance to the rim; d) Probability density plot and weighted average of analysed spots more than 100 µm from the rim.

This project is part of CCFS Theme 2, Earth's Evolution, and contributes to understanding Earth's Architecture.

Contacts: Yu-Ya Gao, Xian-Hua Li, Bill Griffin, Yan-Jie Tang, Norman Pearson, Yu Liu, Mei-Fei Chu, Qiu-Li Li, Guo-Qiang Tang, Sue O'Reilly
Funded by: National Natural Science Foundation of China, Ministry of Science and Technology, MUIPRS, CCFS Flagship Program 1

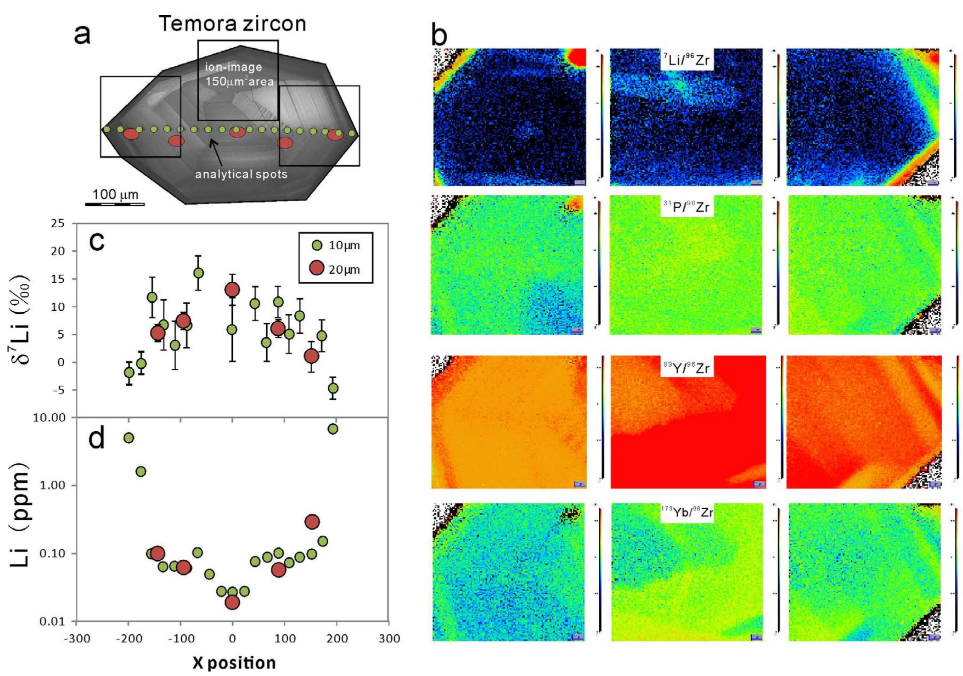


Figure 2. a) The CL image and analytical spots on the Temora zircon; b) ion images of Li, P, Y, and Yb; c) δ^7Li profile through zircon; d) [Li] profile through zircon.

Bridging the gap: using numerical modelling to better understand CO_2 transfer in subduction zones

When it comes to the chemical evolution of Earth, two volatile components stand out as the most geologically significant: water (H_2O) and carbon dioxide (CO_2). These volatiles play a crucial role in every facet of life. Both are key building blocks for organic life on Earth and H_2O has a profound impact on plate tectonics, where it is largely responsible for its mobility.

Volatile recycling in subduction zones, especially of H_2O, greatly affects the physicochemical properties of the overlying mantle (composed mostly of peridotite). As the mantle wedge hydrates, it loses its strength, density and viscosity, and it melts at lower temperatures, as a consequence of metasomatisation. On the other hand, the physicochemical effects of metasomatisation with a carbonic fluid are more subtle and enigmatic. Like H_2O, CO_2 decreases the melting temperature of peridotite. Interestingly, carbonate-rich melts are extremely mobile agents that can extract highly incompatible, heat producing elements (U, Th, and K). This can influence the long-term thermal budget of the mantle, and lead to thermal anomalies at different levels of the mantle. Carbon is also economically significant, important in its elemental form as either diamond or graphite. Lastly, the global carbon cycle and the habitability of our planet depend on the stability of carbon and its residence time in the mantle, the recycling efficiency in subduction zones, and rates of magmatic degassing.

Recently, much effort has been put into understanding the global carbon budget at depths greater than our atmosphere and the crust. Despite these efforts, estimates of carbon concentrations remain largely unconstrained. Experimental and thermodynamic models have been constructed to establish the amount of CO_2 recycled within subduction zones, but these have failed to give a conclusive number.

In this work, for the first time, a binary H_2O-CO_2 fluid has been coupled to a state-of-the-art geodynamic numerical modelling code (I2VIS). This allows us to study how dynamic effects, such as slab roll-back or sedimentary diapirism, lead to decarbonation, carbon recycling, and CO_2 metasomatism in a subduction zone.

This research bridges the dynamics gap, between static thermodynamic modelling and petrological experiments. We accomplished this by testing a wide range of subduction conditions to determine the key parameters that result in decarbonation in the context of a modern subduction zone. The results show that for different subduction regimes, distinctive degassing patterns are observed in time and space. For example, during stable subduction (Fig. 1) little, concentrated CO_2 release is observed, while in more dynamic models, decarbonation is more widely spread through the length of the subducting slab; this difference is a result of non-linear effects that are only seen during 3D and 4D modelling (x,y,z directions and time). We look to further extending our methods beyond decarbonation and to incorporate melting of subducted carbonated components to better understand recycling beyond subarc depths.

This project is part of CCFS themes 2 and 3, Earth's Evolution and Earth Today, and contributes to understanding Earth's Architecture and Fluid Fluxes.

Contacts: Christopher M. Gonzalez, Weronika Gorczyk
Funded by: ARC Linkage Project, UWA SIRF scholarship

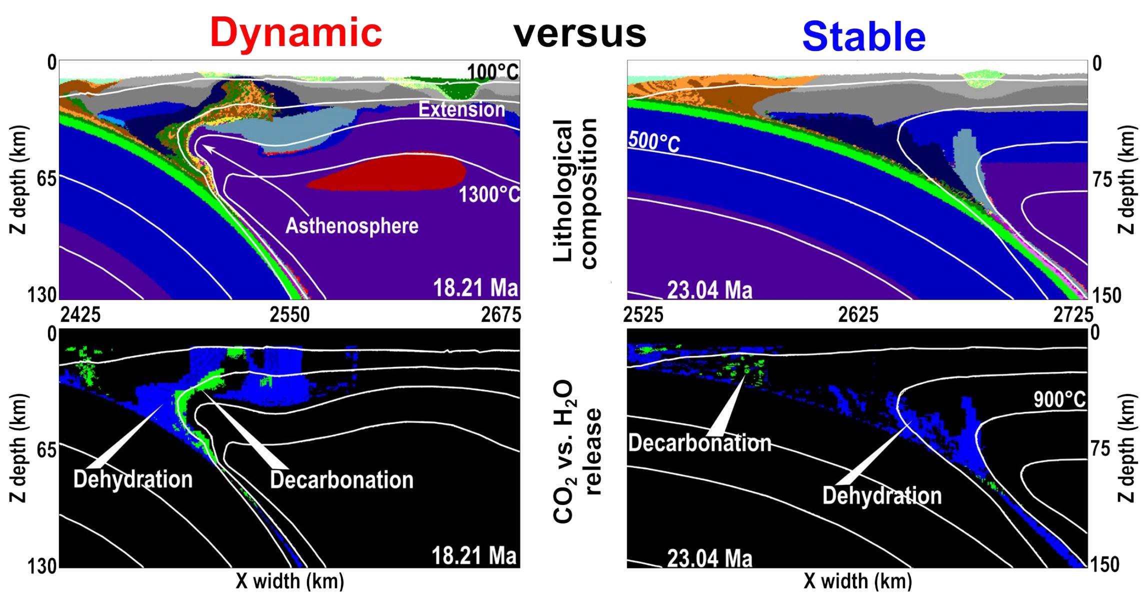


Figure 1. Image showing a comparison of a dynamic subduction zone with a stable subduction zone. In the stable subduction zone, there is neither extension nor sedimentary diapirism. In the dynamic subduction zone, the hot asthenosphere and low pressures result in the release of CO_2. Green and blue colours represent decarbonation and dehydration respectively. Fluids released are able to interact with and metasomatise the overlying lithospheric mantle.

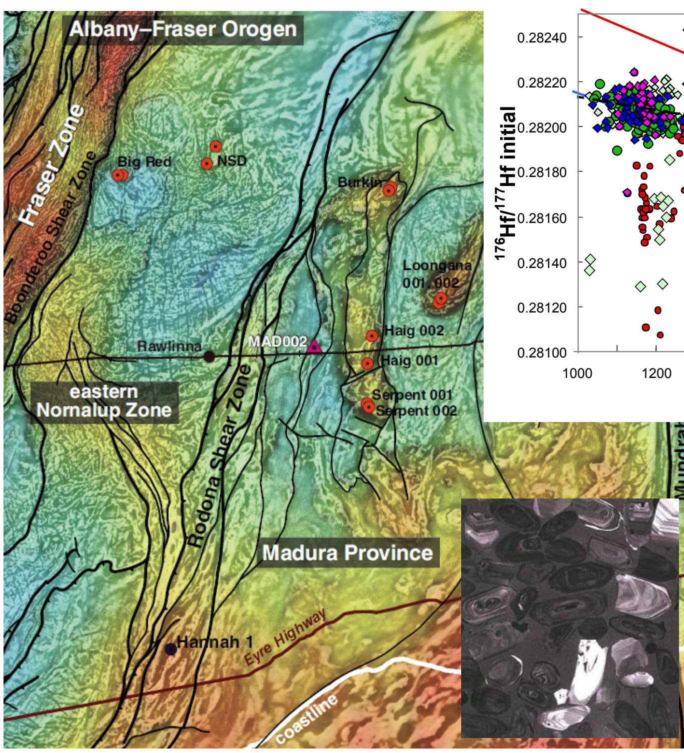
In the deep between the WAC and the SAC

One way of determining the affinity of blocks of crust is to compare their Hf isotopic signatures. Flagship Program 7 aims to generate Lu-Hf isotopic data on previously dated zircon samples, and integrate this with geological, geochemical, and geophysical datasets of the Geological Survey of Western Australia. The research is focused in '*greenfields*' areas where little information presently exists. More than 9000 zircons, from 500 samples, have been analysed during the life of the project. Zircon samples have been selected from dated material in igneous, metamorphic, and sedimentary rocks of the Pilbara Craton, the Eastern Goldfields Superterrane and Murchison Domain of the Yilgarn Craton, the Albany-Fraser Orogen, the Musgrave Province, the Kimberley and Amadeus Basins, the Rudall Province, the Gascoyne Complex, and basement rocks beneath the Eucla Basin. This integrated approach, in which isotopic constraints are viewed in the context of geochemical information, geological mapping, and geophysical datasets has significantly enhanced our understanding of the geodynamics of Western Australia and provided a powerful new dataset to test models of tectonic evolution of the region. This work closely aligns with the UNCOVER initiative that seeks to provide an innovative, structured and nationally coordinated strategic plan to understand the deep geology of Australia, and thus bring competitive advantage to mineral exploration in Australia.

The Precambrian crystalline basement beneath the Eucla Basin represents a frontier '*greenfields*' region; very little is known about its age, composition, and geodynamic evolution. Recently the GSWA Exploration Incentive Scheme co-funded drilling of stratigraphic drill holes that have provided a unique sample set on which a range of cutting edge isotopic techniques has been applied in an effort to reveal its geological evolution and enhance its exploration potential. The exposed mineralised Gawler and Yilgarn cratons are separated by nearly one thousand kilometres of basement that represents a large prospective mineral province, but this region is buried beneath sedimentary basins formed during the development of Australia's southern margin. The mineral potential of this zone between the West Australian Craton (WAC) and the South Australian Craton (SAC) is demonstrated by recent onshore exploration success in both the Tropicana Zone (gold) and the Fraser Zone (nickel). Both these deposits lie in the Albany-Fraser Orogen, which reflects Proterozoic modification of the Yilgarn Craton. The basement substrate that lies further east between the exposed WAC and the SAC remains comparatively unknown.

Isotope geology is perhaps uniquely placed to see through overprinting events to expose both the timing and nature of early crustal formation processes. The Madura Province, the area of basement bounded by the Rodona Shear Zone and the Mundrabilla Shear Zone, lies adjacent to the Albany-Fraser Orogen but preserves a geological history startlingly different from its western neighbor. The Madura Province records two broad phases of magmatic activity. Zircon geochronology from intrusives (gabbros and granites) constrains one phase to 1411-1389 million years, whereas younger granites and gabbros have crystallisation ages of 1180-1125 million years.

Zircon crystals from all these magmatic rocks cluster along an apparent evolution array intersecting the depleted mantle at 1900-2000 million years ago. This suggests that these rocks all reflect dominant generation from a new piece of crust formed at this time. Scatter in this apparent evolution array is clear evidence of new mantle input during the initial phase of 1411-1389 million year magmatism. The isotopic signature of this cont...



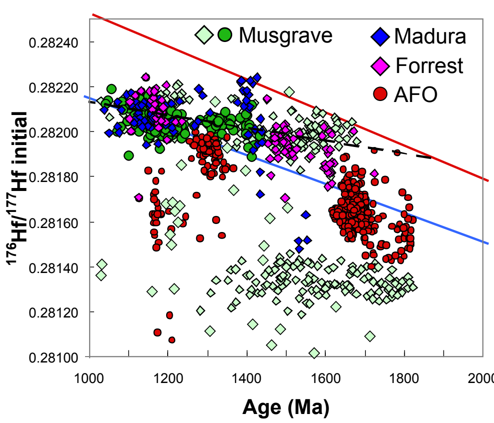


Figure 1. Map of drillhole locations in the eastern Albany-Fraser Orogen and Eucla basement superimposed on a gravity image with geology overlay. Stratigraphic drillholes (triangles) and other drillholes (circles) show the location of material from which Hf isotopes have been acquired. Inset: lower right, CL image of example zircon grains from granite within drillhole sample. Upper right; Hf isotopic evolution plot showing the change in isotopic signature through time and the projection back to a common mix of sources.

region is similar to that of intrusive rocks of the Musgrave Province in Central Australia. Although the age of magmatic crystallisation may be different, the timing of initial formation of crust is similar between the two provinces. In detail we interpret the 1900-2000 million year crustal-formation array to reflect a complex mix of oceanic magma sources with at least three components, including generation of new crust at 1900 million years and 1600-1200 million years, which also involved older Archean material. Such petrogenetic processes match aspects of oceanic arc magmatism and demonstrate that the Rodona Shear Zone was a fundamental suture separating reworked rocks of Yilgarn heritage from a new substrate of oceanic affinity lying between the older crustal blocks. These isotopic data, along with new geochemistry radically refine our understanding of the substrate between the Yilgarn and Gawler cratons, and suggest it reflects Proterozoic oceanic crust.

This project is part of CCFS themes 1 and 2, Early Earth and Earth's Evolution, and contributes to understanding Earth's Architecture.

Contacts: Chris Kirkland, Michael Wingate, Yongjun Lu, Elena Belousova, Catherine Spaggiari, Hugh Smithies, Ed Saunders, Rosanna Murphy, Geological Survey of Western Australia

Funded by: Geological Survey of Western Australia

The hidden Archaean of Volgo-Uralia: a zircon tale

The amount of preserved Archean lithosphere and its global distribution are important for reconstructing Early Earth and to assess its subsequent evolution. However, only *ca* 20% of the presently remaining Archean crust is exposed at Earth's surface; the rest is hidden beneath polar ice sheets and the sedimentary cover of cratons, or forms minor fragments within Proterozoic and Phanerozoic orogenic belts.

Figure 1. The three-segment subdivision of the EEC lithosphere. The red frame outlines the best-investigated part of Volgo-Uralia.

The protocontinent Volgo-Uralia (Fig. 1), which constitutes one-fourth of the East European Craton (EEC, "*Baltica*"), is covered entirely by thick sedimentary deposits. From geophysical studies and the examination of thousands of drillcores, the basement of Volgo-Uralia has been recognised as a vast high-grade terrain with a complex crustal history extending from the Paleoarchean to the Paleoproterozoic.

Our recent studies in Volgo-Uralia have been focused on looking for major events of the Archean crustal evolution employing Sm-Nd whole-rock analysis as well as the ion probe U-Th-Pb (SIMS) and Lu-Hf (LA-ICPMS) to analyse zircons. Particular attention was devoted to the widespread charnockitic rocks, which form large intrusions and contain zircon crystals with notably complex growth histories.

The zircons from one sample, an enderbite, have prismatic magmatic cores up to 2 mm across with oscillatory zoning, which enclose a few smaller zircon grains of an earlier generation (Fig. 2). The cores are surrounded by CL black-and-bright paired bands of curved metamorphic rims. The cores were notably fractured and fragmented prior to the metamorphic event.

The application of several methods of study (U-Pb SIMS/SHRIMP, ICPMS+TE, O- and Hf-isotopes in zircon) revealed (Fig. 3) that:

- The crystallisation age of the magmatic cores is between 3140 ± 7 Ma (SHRIMP) and 3127 ± 46 Ma (LA-ICPMS), while the metamorphic CL-bright rims formed at *ca* 1950 Ma (Fig. 3a and b). Intermediate ages are interpreted as resulting from various degrees of Pb loss caused by high-grade metamorphism.
- The metamorphic recrystallisation of the primary magmatic zircon correlates with depletion in REE, Pb and U which has been observed consistently in each analysed core-rim pair.

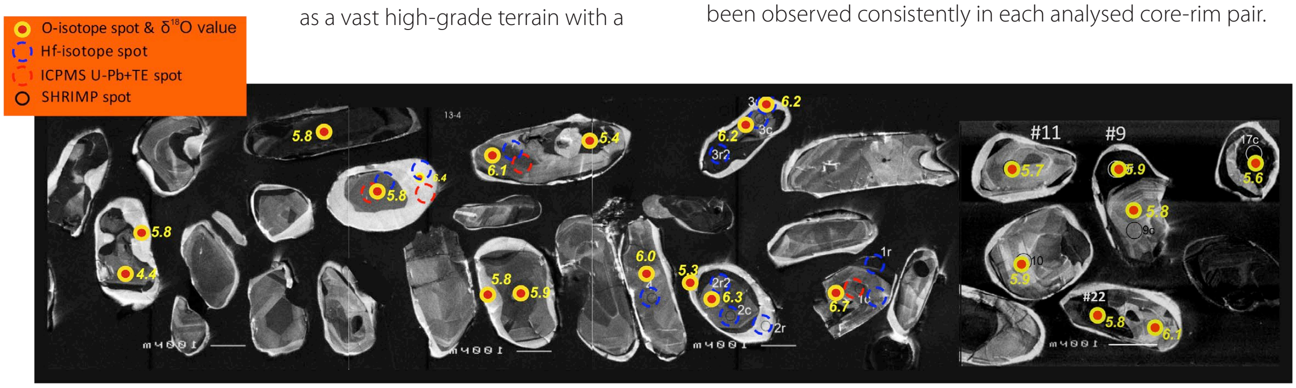


Figure 2. CL images of zircon from the studied enderbite. Gorbatovskaya 51 drill core (2896-2914 m depth), southern Volgo-Uralia.

Characteristically, the metamorphic rims are enriched in P and Hf. Variations of trace elements in the magmatic cores control those in the outermost metamorphic rims.

- The Hf-isotope compositions of the magmatic cores (-3 to -9 εHf) and metamorphic rims (-14 to -28 εHf), and their similar crustal model ages from 3.42 to 3.86 Ga, that the charnockitic magmas were derived by remelting of Eo- to Paleoarchean crust and very little, if any, juvenile material was added during the metamorphic event at *ca* 1950 Ma (Fig. 3c).
- No differences in O-isotopic composition have been detected between the cores and the rims; the $\delta^{18}O$ values vary from ca. 5 to 6.5 (Fig. 2), indicating that the Eo- to Paleoarchean crustal source of the magmas was originally mantle-derived.

From these results we conclude that the Mesoarchean (ca 3.1 Ga) granulitic crust in southern Volgo-Uralia was formed by the reworking of Eo- to Paleoarchean crust. Hf model crustal ages of up to 3.9 Ga found in this region as well as in central Volgo-Uralia suggest that Eo- to Paleoarchean continental crust was widespread throughout Volgo-Uralia. A back-arc setting along an active continental margin may explain the high-T, '*dry and ferroan*' magmatism of the studied charnockitoids. An alternative interpretation may be that deep mantle-plume activity at 3.1 Ga caused mantle underplating, extension of the Palaeoarchean crust and high-T magmatism.

This project is part of CCFS Theme 1, Early Earth, and contributes to understanding Earth's Architecture.

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Funded by: Belousova ARC Future Fellowship

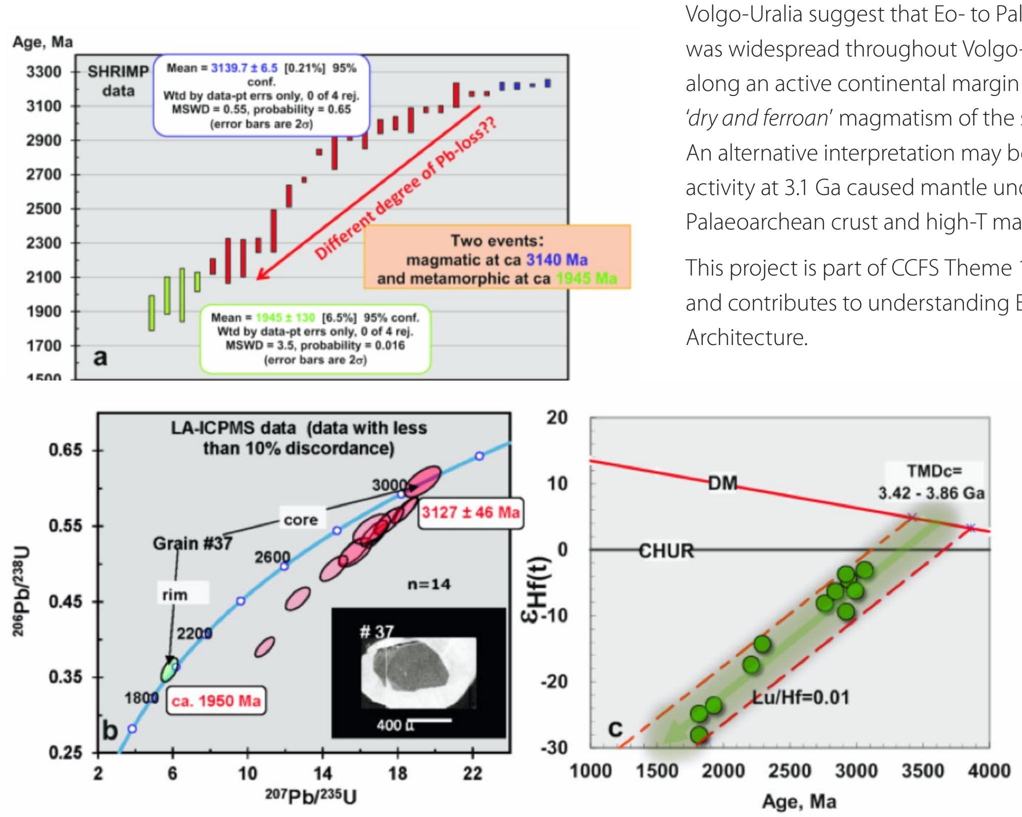

Figure 3. Results of the zircon studies.

Crustal volcanic plumbing systems follow lithospheric boundaries in the Newer Volcanics Province, SE Australia

Intraplate volcanism is a widespread phenomenon, which is generally regarded to be independent of plate tectonics due to its distance from plate boundaries. The Newer Volcanics Province (NVP) is the most recently active intraplate volcanism on the Australian continent. It includes more than 700 eruptions, with the earliest ~4 million years ago and the latest <5000 years ago. The erupted basaltic magmas cover a region more than 19,000 km^2, with an average thickness of less than 60 m. The origins of this intraplate-setting volcanism have drawn considerable attention from geoscientists. The latest research in the region suggests the NVP may originate from combined effects of localised mantle flow and shear flow, which are caused by the Australian plate's drift across a significant lithospheric step; while a nearby hotspot track - presumably fuelled by a plume - may have initiated the volcanism at ~4.5 Ma. However, important questions regarding how the magmas were stored and how they migrated through the crust to the surface remain unanswered, mainly due to the poor constraints on the crustal component of the NVP magmatic system.

In this study, we use ambient noise tomography and probabilistic inversion methods to construct the first local 3D crustal images of the NVP region (Fig. 1) with a general resolution of ~35 km. The images display distinct velocity features near the eastern and western margins of the NVP through the entire crust. This suggests the existence of a lithosphere-scale plumbing system for the migration of melt, associated with the boundary between the Delamerian Orogen and the Lachlan Orogen, which underlies the NVP. In particular, exceptionally high velocities are observed in the middle crust of the Delamerian Orogen, cont...

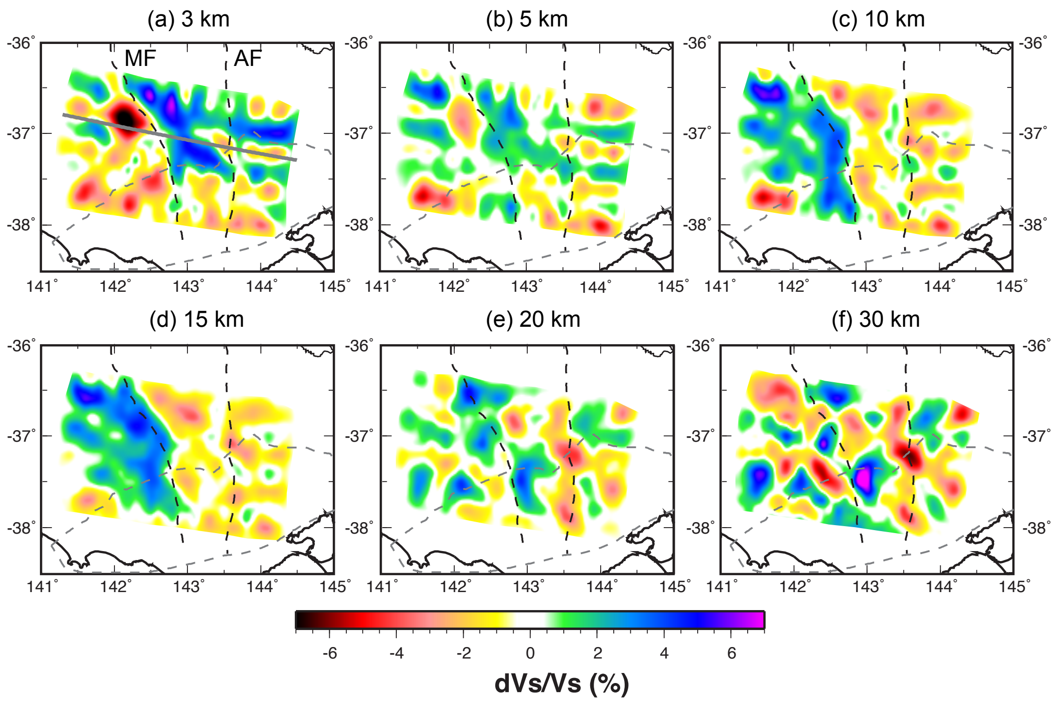

Figure 1. Vsv maps at depths of (a) 3, (b) 5, (c) 10, (d) 15, (e) 20 and (f) 30 km. All depths are relative to sea level. The solid grey line in figure (a) shows the profile location for Figure 2. Abbreviations: MF-Moyston Fault; AF-Avoca Fault.

which are best explained by buried magmatic arcs, resulting from subduction-accretion processes during the Delamerian Orogeny. The model also images small localised velocity reductions in the lower crust in the region where the two distinct lithospheric units meet. The low-velocity zone is spatially correlated with the top of a prominent lithosphere-scale low-resistivity zone, which we interpret to represent intruded magmatic sills with small proportions of melts. The minor volumes of erupted magmas and the small magmatic intrusion seen in the current lower crust indicate a much smaller magmatic plumbing system beneath the NVP (Fig. 2) than that of Yellowstone, which has a mantle-plume origin.

This project is part of CCFS Theme 3, Earth Today, and contributes to understanding Earth's Architecture and Fluid Fluxes.

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Funded by: ARC Discovery Project, Yang ARC Future Fellowship, MQRES scholarship

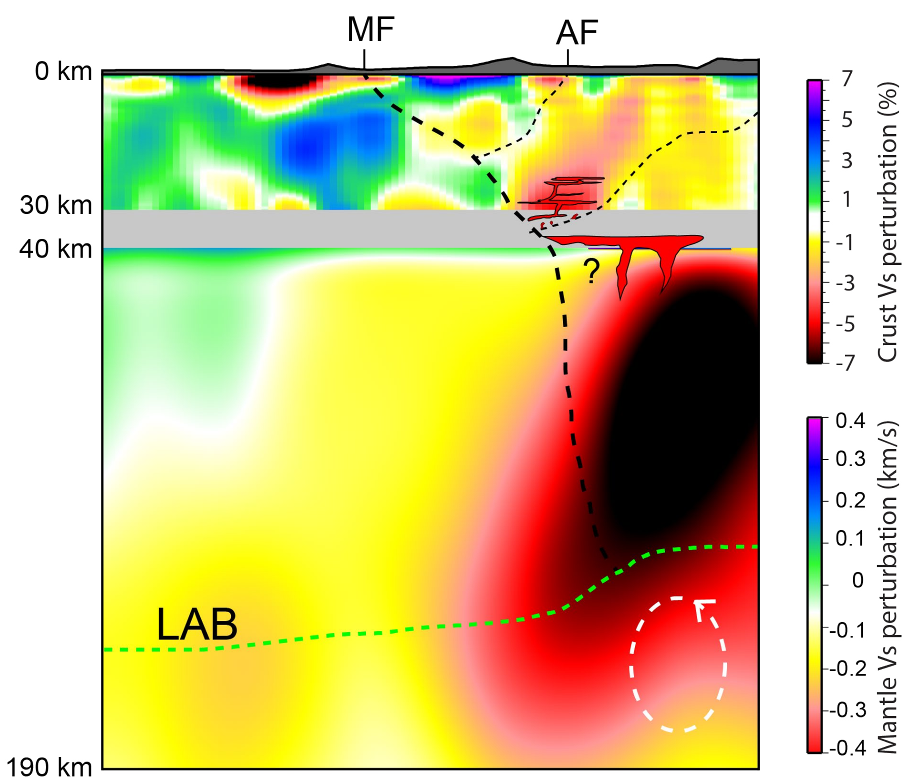

Figure 2. A cartoon to illustrate the accumulated magmatic intrusion in the lower crust beneath the NVP and its connection with the deep lithosphere. The crustal Vs perturbation is relative to the regional average from this study (0-30 km; two times exaggeration relative to the mantle part); while the mantle Vs perturbation is relative to the ak135 model [Kennett et al., 1995] in km/s from Rawlinson et al., [2016] (40-190 km). The white circle illustrates the edge-driven convection from the geodynamic model of D. Rhodri Davies and Rawlinson [2014]. The shaded area on the top of the section represents the real topography, and the depth of the LAB (Lithosphere-Asthenosphere boundary) is an approximation illustration based on the study of D. Rhodri Davies and Rawlinson [2014]. Abbreviations: MF-Moyston Fault; AF-Avoca Fault.

Trace elements in zircon, and the oxidation state of magmas

Many elements in silicate melts and crystalline rocks vary in ionic electric charge (also called ionic *'valence'* or *'oxidation state'*), depending chiefly on availability of oxygen as an electron acceptor; its availability is conventionally represented as *'oxygen fugacity'*, fO_2. Such elements include iron as Fe^{2+} and Fe^{3+}, sulfur as S^{2-}, S^{4+}, and S^{6+}, cerium as Ce^{3+} and Ce^{4+}, europium as Eu^{2+} and Eu^{3+}, uranium as U^{4+}, U^{5+}, and U^{6+}, tin as Sn^{2+} and Sn^{4+}, vanadium as V^{3+}, V^{4+}, and V^{5+}, and molybdenum as Mo^{4+} and Mo^{6+}.

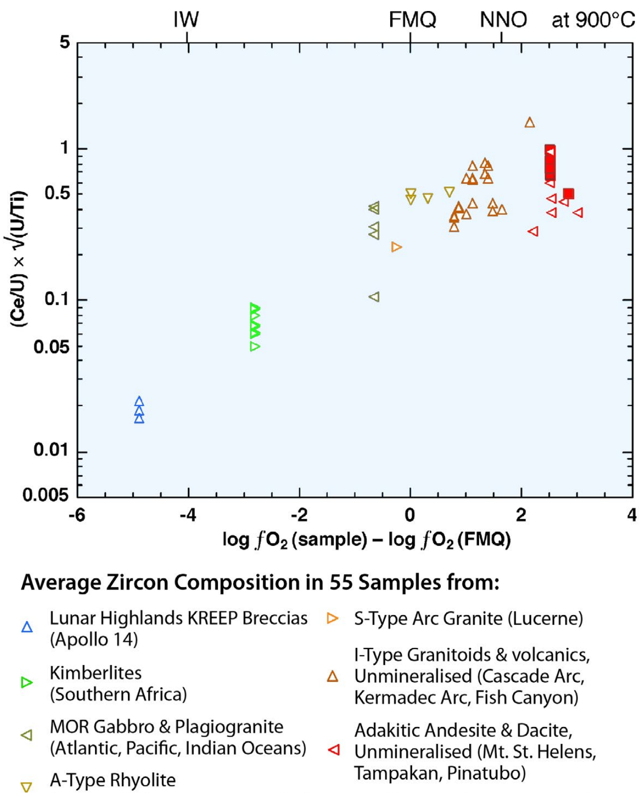

Figure 1. The average composition of several zircons in each of 55 samples is plotted against apparent oxidation state of the silicate melt from which the zircon crystallised. The abscissa variable is log units of oxygen fugacity above or below that of the reference mineral assemblage fayalite+magnetite+quartz, as given in publications that reported values of the oxidation state in the host rocks of the analysed zircons. Solid red symbols represent samples from igneous bodies related to copper ore deposits.

Whether or not a magma can produce an ore deposit of V, Sn, Mo, or Cu depends substantially on the valence of those elements in the magma. Major controversies surround the oxidation state of the early Earth's upper mantle and surface 4.5-2.3 billion years ago, and to what degree the oxidation state of Earth's mantle has been affected by cycling of materials from the surface into the planetary interior over the past 2.3 billion years, as Earth's surface became more oxidised due to production of oxygen by photosynthetic microbes.

Electron transfer among elements is fast, so all elemental oxidation/reduction couples in silicate melts are instantaneously interactive; therefore, a measure of the valence ratio of one element is, in principle, a constraint on the valence ratio of every other element. Zircon, $Zr^{4+}Si^{4+}O_4$, is a common minor mineral in igneous rocks and preserves a record of the oxidation state of its parent silicate melt and of the melt's source because (1) it takes in trace amounts of other elements of variable electric charge that substitute for Zr^{4+} and Si^{4+}, and (2) it is extremely resistant to chemical modification after crystallisation, so its record of oxidation state can be preserved for billions of years of deep burial at sub-magmatic temperatures. Over the past decade, scores of published papers have reported estimates of the relative oxidation state of magmas using the ratio Ce^{4+}/Ce^{3+} in zircon. Experimental studies demonstrate that Ce^{4+}/Ce^{3+} in silicate melts and zircon vary with magma oxidation state, but the ratio in zircon is even more sensitive to variation of temperature, because Ce^{3+} is 18% larger than Ce^{4+}, and 36% larger than Zr^{4+}, so substitution of Ce^{3+} represents a misfit in both size and charge. This requires coupled substitution of another misfit ion, usually either phosphorus P^{5+} for Si^{4+} or OH^{1-} for O^{2-}. Therefore, the Ce^{4+}/Ce^{3+} ratio in zircon is extremely sensitive to thermal contraction of the zircon crystal lattice, and the temperature dependence usually overwhelms the fO_2 signal being sought. We find that in nearly all publications in which zircon Ce^{4+}/Ce^{3+} was inferred to represent magmatic oxidation state, the variations in Ce^{4+}/Ce^{3+} were actually due almost entirely to variations in temperature.

To formulate a zircon sensor of the oxidation state of the parent magma that is relatively insensitive to temperature variation, the sensor ions need to have the same ionic charge and nearly the same size. The ratio Ce^{4+}/U^{4+} in zircon fits those requirements. However, the zircon inherits a distorted version of this ratio from its parent melt, biased by partition coefficients. As the parent melt crystallises, its Ce^{4+}/U^{4+} ratio decreases due to selective removal of some Ce^{4+} by other minerals that start crystallising before zircon. So the zircon indicator of magmatic oxidation state needs to account for the stage of chemical evolution of the parent magma. The ratio U/Ti in zircon works well as a qualitative indicator of the stage of chemical evolution of the parent magma. Figure 1 illustrates the potential of our new indicator of magmatic oxidation state, using our microbeam chemical analyses of zircons in eight igneous suites and many compiled from published literature. For each of these igneous suites, independent estimates of magmatic oxygen fugacity, fO_2, are available.

This study is an outcome from the ongoing Flagship Program 2.

This project is part of CCFS Themes 2 and 3, Earth's Evolution and Earth Today and contributes to understanding Fluid Fluxes.

Contacts: Robert Loucks, Marco Fiorentini, Yongjun Lu

Funded by: CCFS Flagship Program 2

Resolving the controversy of Earth's oldest fossils

A few 10 km outside Marble Bar in the Pilbara region of Western Australia lies one of the more famous sites for scientific research in Australia. Around a quarter of a century ago, UCLA palaeontologist JW Schopf discovered tiny filaments preserved within a ~3.5 Ga silica-rich rock, the so-called Apex chert. These were interpreted as the fossilised remains of primitive filamentous bacteria and thus thought to constitute the earliest known evidence for life on Earth.

With the technology available to researchers at that time this was a reasonable interpretation. The sizes of the filaments (mostly 1-20 µm in diameter) were comparable to known filamentous bacteria and they had an internal structure that resembled multiple cells joined in chains.

During the following decade these filaments became embedded in both the textbook and popular science literature as "*Earth's oldest microfossils*" and were also heralded as the standard against which other possible signs of ancient (or even extra-terrestrial) microbes should be judged.

Everything changed in 2002 when a team led by Oxford palaeobiologist Martin Brasier questioned the authenticity of the microfossils. Brasier and colleagues had re-interpreted the geological setting of the filaments, demonstrating that they were trapped in rocks that formed at high temperatures during volcanic activity, casting doubt on Schopf's initial interpretation.

Re-examination of the filaments under the microscope revealed that some appeared to branch and others followed the edges of mineral crystals. These new findings led the Brasier group to propose that the filaments were not microfossils, but merely bits of carbon, arranged in roughly filamentous patterns around crystal boundaries, probably formed by hot fluids.

In the ensuing decade or so the "*Apex microfossil debate*" has been intense. Although it is now accepted that the geological setting probably is hydrothermal, this has not diminished the Schopf group's belief in the authenticity of the microfossils. They now suggest that the filaments are fossils of heat-loving (thermophilic) bacteria, similar to those found around deep-sea hydrothermal vents today. On the other side of the debate, the Brasier group presented more detailed geological and microscopic analysis consistent with the filaments being non-biological artefacts. A scientific stalemate had been reached.

New work at CCFS led by ARC Future Fellow David Wacey in collaboration with the late Professor Brasier has finally ended the stalemate. Wacey and colleagues used high spatial resolution electron microscopy techniques to investigate the detailed structure and chemical composition of the filaments. This research, published in two parts in Proceedings of the National Academy of Sciences (*CCFS Publication #528*) and Gondwana Research (*CCFS Publication #663*) has confirmed that the Apex filaments are not microfossils, but instead are mineral artefacts, comprising stacks of silicate grains onto which later carbon was adsorbed.

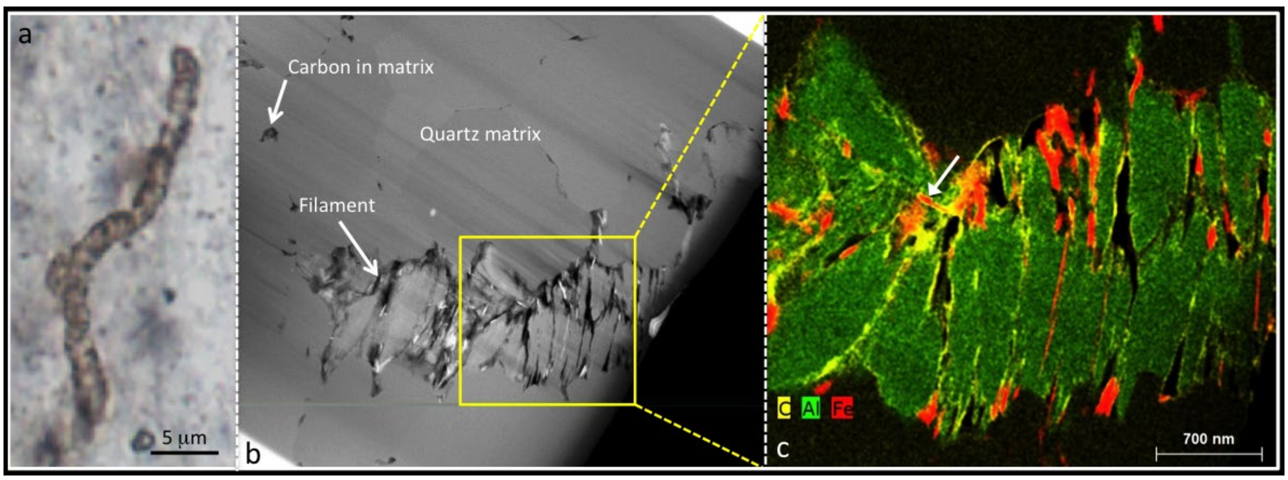

Figure 1. a) Typical filament from the 3.46 Ga Apex chert viewed using light microscopy. b) Transmission electron microscopy image of a filament from the Apex chert. c) False colour three-element overlay map of area boxed in (b). The filament comprises stacks of sheet-like phyllosilicate grains (green) with carbon (yellow) and iron (red) interleaved between some of the sheets. This distribution of phases is incompatible with a biological origin for the filament. In places, carbon completely coats the iron phase (arrow) suggesting carbon was the last phase to become associated with the filaments.

The new data provide a picture of the morphology and chemistry of the filaments at a spatial scale up to one hundred times better than previous studies. At this scale it becomes apparent that the filaments are made of hundreds of plate-like grains of a potassium and barium rich silicate mineral, similar in appearance to common mica. Although carbon is present in the filaments, its distribution is incompatible with any known biological morphology (Figs. 1 and 2).

Today mica-like minerals are used to clean up oil spills due to their very high capacity to adsorb hydrocarbons, and the carbon in the Apex filaments probably was arranged by a similar process. While the lower-resolution techniques previously employed allowed a potential biological interpretation, the new high-resolution images show that the arrangement and distribution of the carbon within the minerals does not support the biological hypothesis.

Previously reported *'cellular compartments'* actually have very inconsistent lengths, and length/width ratios that match crystal growth patterns but are unlike any known microbial cells. The carbon is found to have entered the filaments after the formation of the surrounding minerals, again inconsistent with it being the *in situ* remains of bacteria (Fig. 1).

The field of early life research is fraught with difficulty. Data initially interpreted as biological in origin is often reinterpreted at a later date as having a geological explanation. As new analytical techniques become available, accepted paradigms may have to be questioned.

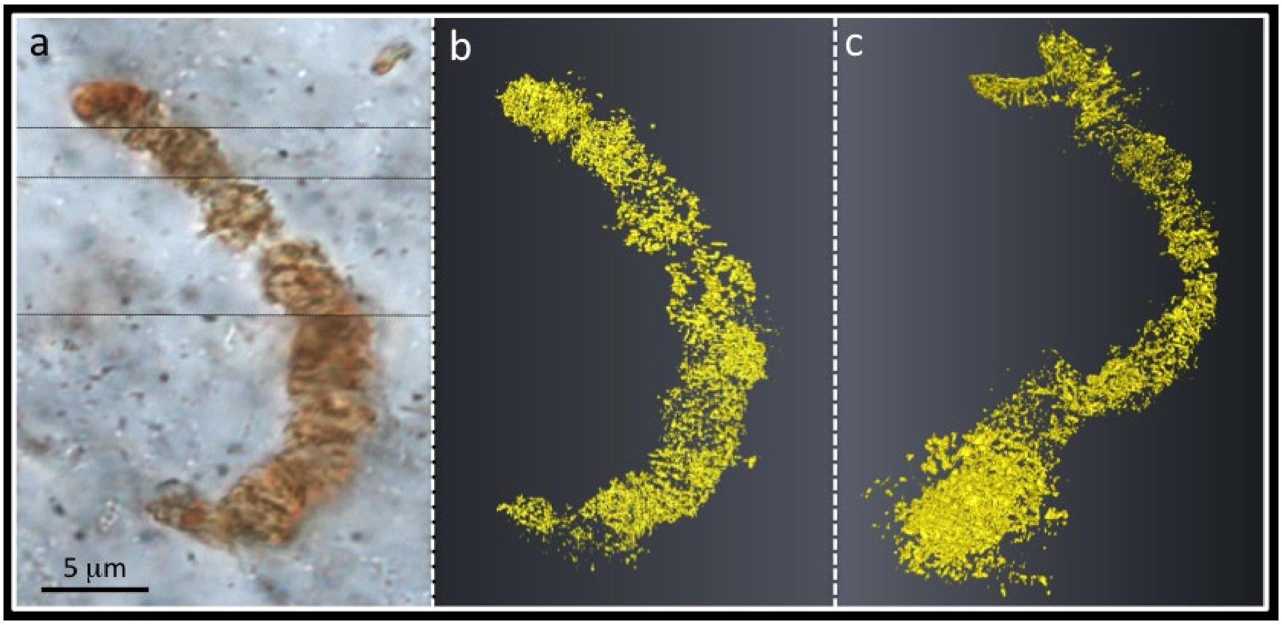

Figure 2. 3D reconstruction of an Apex filament. a) Transmitted light photomicrograph of chosen filament. b) 3D visualisation of carbon from nano-tomography images through the filament, shown in the same orientation as (a). c) 3D model rotated to show small branch extending down below the main body of the filament, not seen in (a-b), and incompatible with a primitive bacterial morphology.

This research does not really move the goalposts for when life first originated on Earth, since there are robust microfossils only a few million years younger than the Apex material. However, it emphasises that not everything that looks like life really is life. Perhaps most importantly it shows that microstructures that appear to tick all the boxes for biology when examined down to the micrometre scale, can fail some of these same criteria when examined at the sub-micrometre scale. This may usher in a new way of analysing possible signs of life in the future, on Earth or further afield.

This project is part of CCFS Theme 1, Early Earth, and contributes to understanding Fluid Fluxes.

Contact: David Wacey

Funded by: ARC Future Fellowship

Mingling processes in Cretaceous Angolan kimberlites

Kimberlites are volcanic rocks which are best known as potential diamond mines. Indeed, it was the deep source of the kimberlitic magmas, as well as their rapid emplacement, that turned them into targets for diamond exploration. Angola is ranked fourth in Africa in terms of kimberlite abundance, but due to its recently troubled history, very little work has been carried out to characterise kimberlites in this country. Fortunately, a collaboration between University of Barcelona, Universidade Agostinho Neto (Luanda), CATOCA Company and CCFS has given access to several kimberlites of the Lunda Norte province (NE Angola) and allowed us to characterise them.

Kimberlites are heterogeneous rocks, with variable contents of groundmass minerals, xenocrysts and xenoliths entrained by the magmas during their ascent towards the surface. With this complex history, dating kimberlites and characterising their source is challenging. Perovskite ($CaTiO_3$) is a ubiquitous minor phase (<10%) in kimberlites and crystallises directly from the magma. It also is relatively resistant to weathering and *cont...*

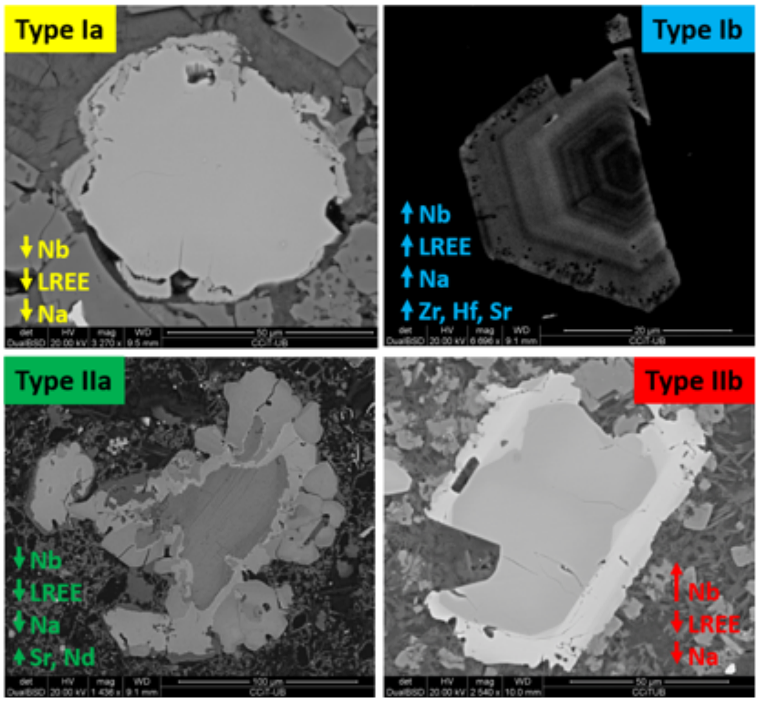

Figure 1. BSE-SEM images of the 4 textural types of perovskite found in the Angolan kimberlites, as well as their main compositional features. Primary perovskite (Type Ia) is typically unzoned, altered to TiO_2 and contains no inclusions. In contrast, primary perovskite (Type Ib) is commonly euhedral, shows oscillatory zoning, has tiny inclusions near the grain boundaries and remained unaltered. Secondary perovskite usually occurs as reaction-induced rims on ilmenite and other Ti oxides (IIa), although in some cases a fourth generation of perovskite was found as thin Nb-rich overgrowths (IIb) on previously crystallised perovskite.

a main carrier of U, Th, Sr and Nd. Therefore, over the last decade, perovskite has become widely used for both age determination and characterisation of the sources of kimberlitic magmas.

This study is the first work on *in situ* U-Pb geochronology and Sr-Nd isotope analysis of perovskite grains from Angolan kimberlites, and is based on a detailed petrographic and chemical study of perovskite from six pipes in the Lunda Norte province.

Four types of perovskite were identified, differing in texture, major- and trace-element composition, zoning patterns, type of alteration and the presence or absence of inclusions (Fig. 1). Primary groundmass perovskite is either as anhedral, Na-, Nb- and LREE-poor perovskite (Type Ia); or euhedral, strongly zoned, Na-, Nb- and LREE-rich perovskite (Type Ib). Secondary perovskite occurs as reaction rims on ilmenite (Type IIa) or as high-Nb (up to 10.6 wt% Nb_2O_5) rims on primary perovskite (Type IIb). The occurrence of these four types of perovskite reflects a complex, multi-stage process that involved mingling of compositionally different melts.

U-Pb dating of these perovskites yielded Lower Cretaceous ages for all the studied kimberlites: Mulepe 1 (116.2 ± 6.5 Ma), Mulepe2 (123.0 ± 3.6 Ma), Calonda (119.5 ± 4.3 Ma) and Cat115 (133 ± 10 Ma). Perovskite in the other two kimberlites shows higher alteration and Pb loss, and as a result only approximate ages could be obtained for the Lucapa 1 (135 Ma) and Lucapa 2 (156 Ma) kimberlites (Fig. 2).

Our results indicate that kimberlite magmatism in the Lunda Norte province (115-130 Ma) peaked around 120 Ma, coinciding with the breakup of the Gondwana supercontinent. Kimberlite emplacement was related to reactivation of NE-SW deep-seated faults (>300 km deep), or cryptic continental corridors, which represent the continuation of oceanic fracture zones. The Sr_i and εNd_i values reported in the perovskites are in good agreement with the published data for on- and off-craton South African Group I kimberlites, as well as with the petrological observations.

This work is part of CCFS Themes 2 and 3, Earth's Evolution and Earth Today, and contributes to understanding Earth's Architecture and Fluid Fluxes.

Contact: Montgarri Castillo Oliver

Funded by: SGR444 (Universitat de Barcelona), Fundació Pedro Pons (UB), CATOCA Company, CCFS Flagship Program 1

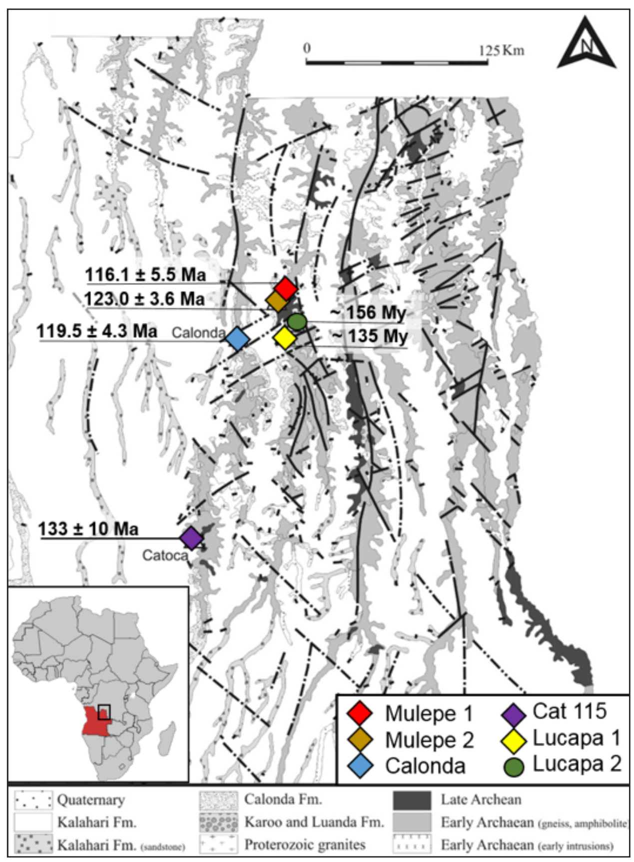

Figure 2. Location of the Angolan kimberlites studied in this work, as well as their emplacement ages.

In search of high flux magma conduits with new structural mapping tools

Magmatic Ni-Cu-PGE sulfide systems account for ~60% of world Ni production and include some of the most valuable mineral camps on earth such as Noril'sl-Talnakh (Russia), Voisey's Bay (Canada), and Jinchuan (China). There is consensus that Ni-Cu-PGE sulfide deposits are associated with high-flux magma channels that transport mantle-derived mafic and ultramafic melts into the crust. However, the mode of emplacement and self-organisation of these magma feeder systems remain poorly understood in the context of magmatic-sulfide systems.

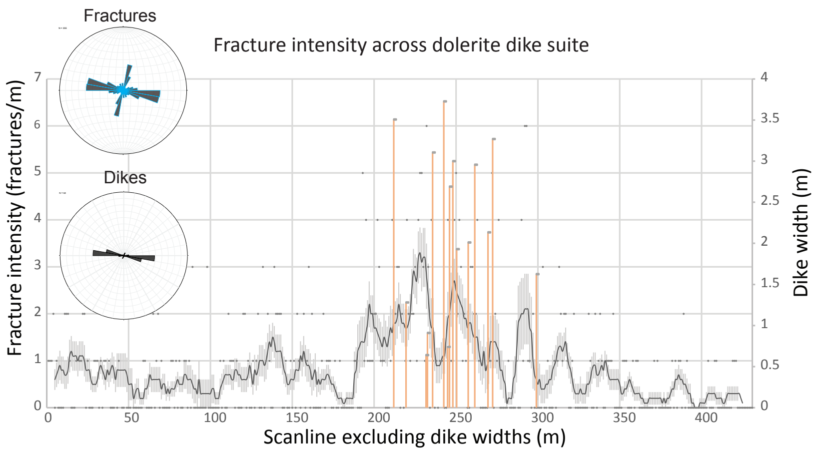

Figure 1. Moving average of fracture intensity surrounding a suite of dolerite dikes. Location of individual dikes shown in orange with dike widths on right-hand axis. Variance in average fracture intensity shown as standard error.

Important questions regarding magma emplacement include:
How is magma dispersed in large mafic systems?
How do propagating intrusions interact with country rocks at micro- to macro-scales?

As a first step toward addressing these questions, we examine how magma-carrying fracture networks develop and propagate. Where data is available for intrusion-hosted Ni-Cu-PGE deposits, host rock anisotropy has been shown to be a first-order control on intrusion geometry (Saumur et al., 2015). To further investigate magma-host rock interaction an innovative technique is employed using unmanned aerial vehicles and photogrammetry to map and structurally analyse a mafic intrusion network in 3D at very high resolution (1 cm to 1 pixel, or finer). Structural data are extracted from a digitally reconstructed outcrop model using a least squares regression analysis. The accuracy of structural measurements extracted from the model has been successfully validated with conventional field measurements. This method has the advantage of rapid and accurate data collection along spatially rectified traverses, referred to as scanlines.

The 3D mapping technique has been applied to a suite of 21 dolerite dikes emplaced in Mesoproterozoic granitic rocks along the south coast of Western Australia. The dikes are from <1 m to 5 m wide and closely spaced with a cumulative thickness of 33 m over an across-strike distance of 105 m. Dikes occupy vertical fractures that strike 075°-125°. Structural data is collected along scanlines oriented perpendicular to the mean strike direction of the dike suite. Scanline data reveal fracture intensity (number of fractures per fixed unit length) in granitic wall rocks within the dike suite to be on average 2.2 times higher than the background fracture intensity in the host rock. Though empirical data from other dike suites are not available, the fracture intensity difference is compatible with mechanical predictions of stress changes induced by propagation of an over-pressured blade-shaped intrusion (*Rubin and Pollard, 1988*). Such investigations of well exposed mafic intrusions are a first step toward understanding the mechanisms and dynamics of magma transport leading to the development of high-flux conduits.

This project is part of CCFS Theme 3, Earth Today, and contributes to understanding Earth's Architecture and Fluid Fluxes.

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Funded by:
Fiorentini ARC Future Fellowship, CSIRO Mineral Systems Flagship, CCFS Flagship Program 2

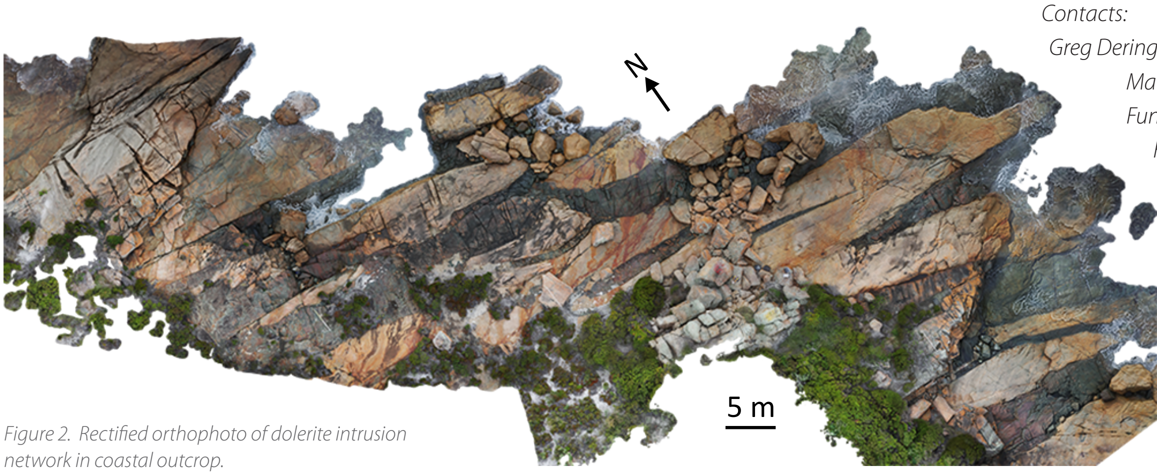


Figure 2. Rectified orthophoto of dolerite intrusion network in coastal outcrop.

The hot-and-cold Earth system

Controversy surrounds the evolution of planet Earth through deep time, specifically whether the crust has grown uniformly over time or in pulses associated with the supercontinent cycle. New research at CCFS has set out to investigate this problem by combining global datasets of geochemical proxies that reflect both the subduction process, and the production of magmas from juvenile mantle (non-subduction-related magmatism). Proxies include oxygen isotopes and incompatible trace elements of dated magmatic rocks (subduction-recycling proxy), and Hf-isotope compositions of dated zircon crystals (mantle magmatism proxy).

The results clearly show, in a statistically meaningful way, that the supercontinent cycle has been an important contributor to crustal growth since ca 3.2 billion years ago (Ga), when modern-style plate tectonics is now widely thought to have commenced (Fig. 1). More importantly, the supercontinent cycle appears to have evolved over the course of Earth history, with ever longer cycles and increasing amounts of crustal recycling up to 1 Ga, followed by decreasing amounts of crustal recycling thereafter. Periods of supercontinent formation were accompanied by widespread subduction of old, cold oceanic lithosphere and recycling of continental crust. Periods when supercontinents were amalgamated and then split apart were characterised by lower rates of crustal recycling and increased levels of juvenile mantle magmatism; the latter higher minima in Hf isotope values.

A key feature of the data that links with the geological record is that Earth operated in a '*Conditioned Duality*', with periods of rapid subduction and supercontinent amalgamation characterised by pulses of hot mantle magmatism and extensive crustal growth and rec-cling, followed by pulses of amalgamated and rifting supercontinents characterised by cool mantle and low rates of crustal growth and recycling (Fig. 2). Periods of warm mantle are characterised by the concentrated global eruption of mantle-derived melts (e.g., komatiites, and emplacement of large igneous provinces, such as the Bushveld magmatic province). But the widespread subduction of old cold oceanic lithosphere, and the associated piling-up of slab graveyards across the core-mantle boundary, led to mantle cooling when supercontinents were amalgamated. It was only after the mantle had warmed up again - through a combination of conduction from below and insulation from above - that the supercontinents were able to split apart and the next supercontinent cycle commence.

These pulses of rapid crust formation lead to the idea of '*crustal oversteps*', whereby too much crust forms during pulses of supercontinent formation relative to where the planet is in terms of overall heat loss. Thus, crustal recycling and renewed crustal

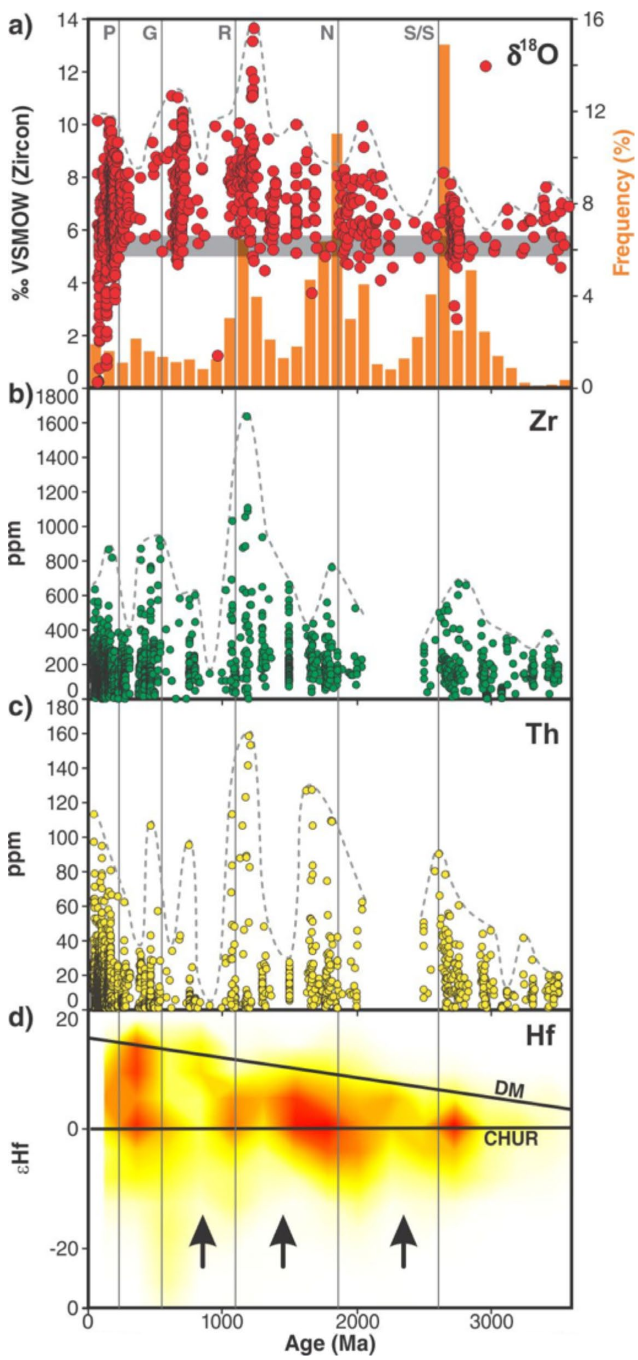


Figure 1. Evolution plots of isotopic and trace element geochemistry over time (age in millions of years (Ma)). A) $\delta^{18}O$(VSMOW) in zircon grains (red dots) from a global compilation plotted on a background of zircon ages of juvenile crust (data from Condie, 1998). Grey horizontal bar denotes average mantle values of oxygen isotopes in zircon (from Valley et al., 2005). B) and C) Concentrations of incompatible trace elements (Zr and Th) in dated igneous rocks from global geochemical datasets (from Van Kranendonk et al., 2015). D) Contour density plot of the number of Hf isotopic values of dated zircons from Belousova et al. (2010): CHUR = chondrite normalised uniform reservoir; DM = depleted mantle. Black arrows point to periods with minimum negative Hf isotopic values, representing pulses of minimal crustal recycling during times of supercontinent disaggregation. Red lines on the εHf vs time diagrams denote the variations in isotopic signature of crust, becoming highly negative during periods of supercontinent amalgamation as a function of increased crustal recycling, and returning to positive (juvenile) values during periods of renewed mantle magmatism accompanying supercontinent dispersals.

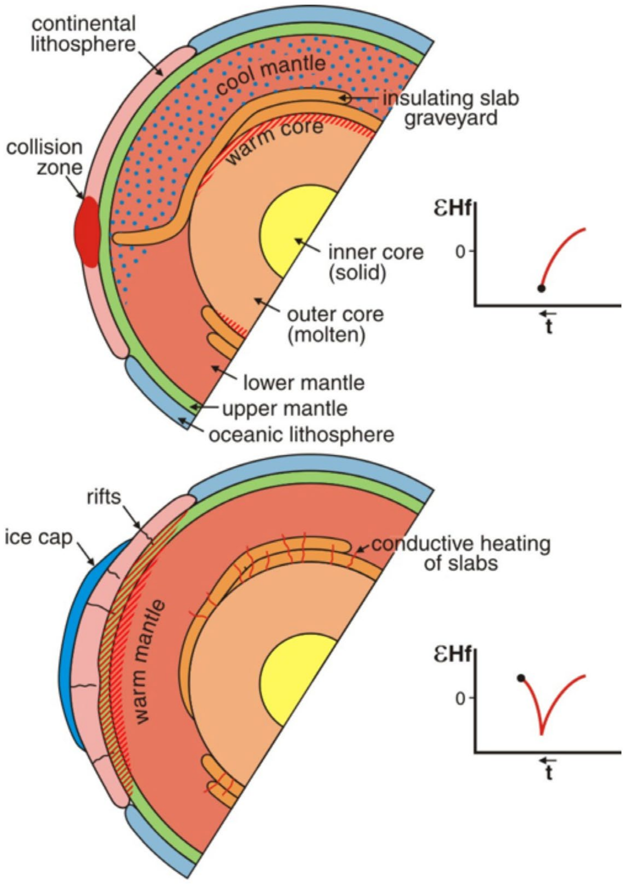


Figure 2. Schematic representation of the two-state Earth in hemispherical cross-sections. Top panel shows a period of supercontinent amalgamation, when widespread subduction causes mantle cooling through a combination of thermal cooling, arising from the introduction of cool oceanic lithosphere, and insulation of the mantle from core heat, through the presence of thick slab graveyards at the core-mantle boundary. Bottom panel shows a period of supercontinent disaggregation, when conductive heating from the core and supercontinent insulation cause mantle warming. Note that widespread glaciations (ice cap on bottom panel) lags behind mantle cooling is a function of the conductive cooling of the crust.

growth is delayed until the volume of crust matches the heat coming out of the mantle. With each stage of supercontinent assembly and related mantle cooling, the tessellation geometry changed in a stepwise manner, reflecting the overall decrease in planetary heat over time. Our current geometry of 12 plates matches a stable dodecahedral tessellation (T3 on Fig. 3), where-as previous steps included less stable geometries with more and smaller plates. However, in the Archean, a stable tessellation of N=32 plates existed as a truncated icosahedron of 12 pentagonal and 20 hexagonal plates of roughly equal size.

This project is part of CCFS Theme 2, Earth's Evolution, and contributes to understanding Earth's Architecture and Fluid Fluxes.

Contacts: Martin Van Kranendonk, Chris Kirkland
Funded by: CCFS Flagship Program 4, UNSW, Curtin University

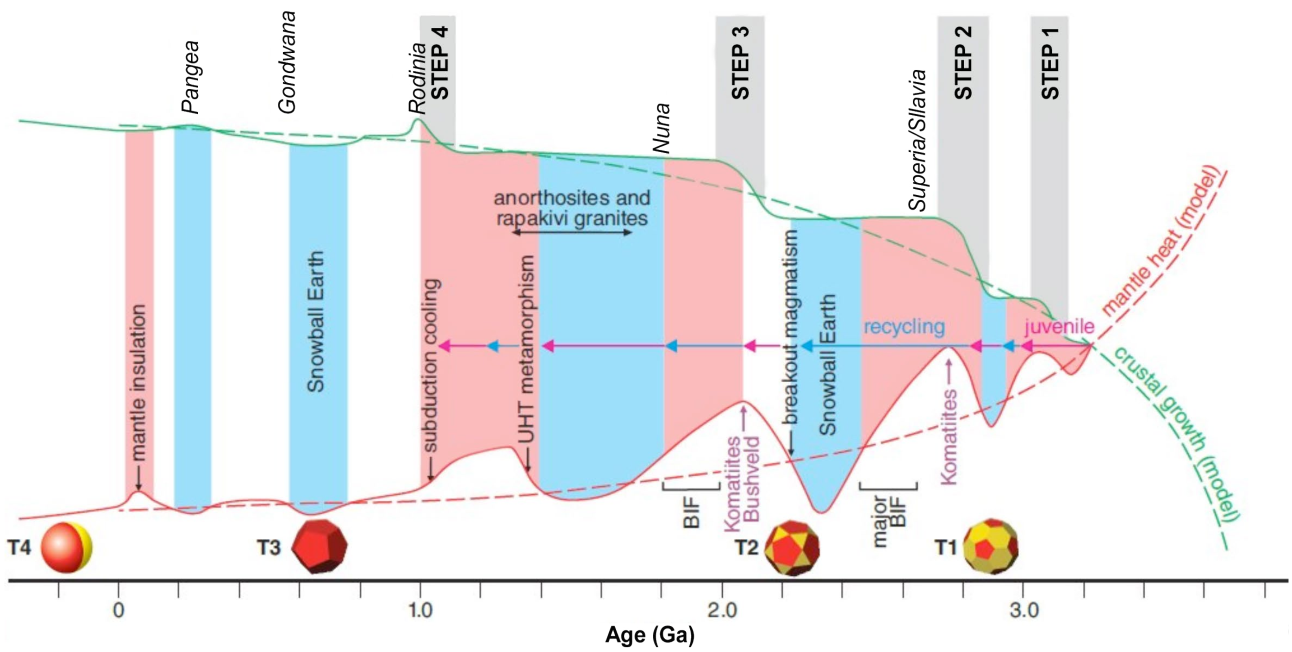
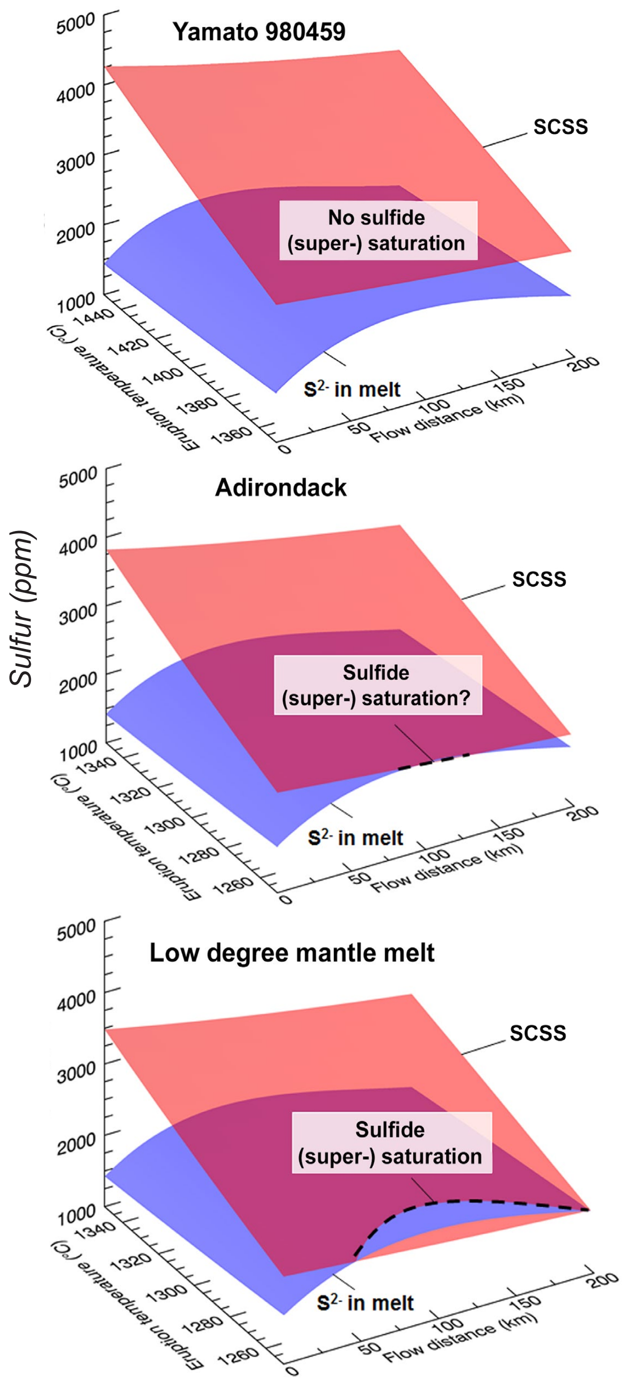


Figure 3. Schematic model of Earth evolution, showing modelled (dashed red curve) and inferred (smooth red curve) heat loss, idealised and inferred crust formation (dashed and smooth green curves, respectively) and tessellation states (T1 to T4). Crustal overstep events (Steps 1-4) are when the volume of continental crust exceeds the ideal volume for a given value of ideal heat loss, and occur immediately following supercontinent amalgamation events (names of supercontinents in italics above crustal growth curves). Heat loss is inferred to vary episodically above the idealised curve, with hot periods (coloured pink) identified by voluminous komatiite and Large Igneous Province (e.g., Bushveld) magmatism, and anorthosite-rapakivi granite magmatism, and cooler periods identified by ice ages (coloured blue). Pink arrows denote pulses of rapid juvenile magmatism; blue arrows periods of predominant crustal recycling. BIF = banded iron-formation; UHT = ultra-high temperature metamorphism.

Mineral exploration on Mars

The geology of Mars is surprisingly well documented. Orbiting satellites have surveyed the Martian surface via hyper-spectral imaging systems, Landers and Rovers have directly observed and analysed the Martian surface, and numerous Martian meteorites are available to the scientific community. The emerging picture is that the basaltic to ultramafic lavas that presently cover a large portion of the Martian surface may have had physical and chemical characteristics akin to the komatiites and ferropicrites that erupted on Earth during the Archean and Proterozoic eons.



As komatiites and ferropicrites are significant hosts to high-grade Ni-Cu-PGE sulfide mineralisation, the question arises as to whether similar deposits can be found on Mars. Unfortunately, sulfides cannot be easily detected by means of remote sensing (e.g. via hyper-spectral imagery onboard satellites), and no evidence for significant sulfide enrichment has been found through the limited analysis of magmatic rocks at landing sites or through the study of Martian meteorites. Hence, we have investigated the potential loci for Ni-Cu-PGE sulfide mineralisation through the application of predictive mineral system targeting.

On Earth, komatiites and ferropicrites are thought to have been emplaced as turbulent lava flows along conduits and channels with high thermal and mechanical erosion rates. The erosion and assimilation of sulfur-rich substrates probably triggered batch segregation of sulfides and their accumulation in basal units. Similarly, a recent study carried out within the framework of CCFS Flagship Program 4 (*CCFS Publication #508*) has suggested that the thermal and mechanical erosion of widepsread sulfate-rich sedimentary substrates may have been a common mineralising process in erosive Martian lava flows. However, several mechanisms in this mineralisation model remain unconstrained. In fact, even if the erosive nature of some Martian lava flows is reflected in the occurrence of carved channels, recent numerical studies aimed at exploring their erosive capability did not consider the diverse array of eruption parameters and of potentially sulfate-rich sedimentary substrates, and focused on basaltic bedrock. Most importantly, both the efficiency of Martian lavas to assimilate and reduce sulfate (i.e., S^{6+}) to sulfide (i.e., S^{2-}), rather than the dissolving sulfur as S^{6+}, and the degassing of sulfur-bearing gases during lava emplacement (i.e., S_2, H_2S, SO_2), remain unconstrained.

Our ongoing study aims to refine existing mathematical lava-erosion simulations for turbulent flows, thermodynamic volatile degassing models, and formulations on the stability of sulfides, into a semi-quantitative model for sulfide batch segregation and the formation of komatiite-type sulfide mineralisation in Martian lava flows. We have examined a series of scenarios in which turbulent mafic to ultramafic melts (Fig. 1) with varied chemical

Figure 1. Modelling results for selected unidirectional, gravity-driven steady Martian lava flows in the turbulent flow regime, in the diagram flow distance from the vent (x-axis), eruption temperature (y-axis) and sulfur (i.e. sulfur capacity at sulfide saturation, SCSS, and actual sulfur in the melt). Lava cooling is simulated for convective heat loss to the base and top of the flow, as well as energy consumed due to thermal erosion of substrate and progressive crystallisation of the flow. Several algorithms are integrated to simulate the evolving flow characteristics (e.g., lava temperature, composition, Reynolds number, viscosity, heat transfer coefficient, mechanical and thermo-mechanical erosion rate) at incremental steps downstream. Batch segregation of sulfides may commences when the SCSS (red) and the sulfur in melt (blue) trajectory intersect. The lava types considered are selected Hesperian to Amazonian mantle melts constrained based on a) the study of the olivine-phyric Shergottite meteorite Y 980459, b) the Adirondack-class basalt at the Gusev Crater landing site, and c) low-degree melting experiments on the Martian mantle.

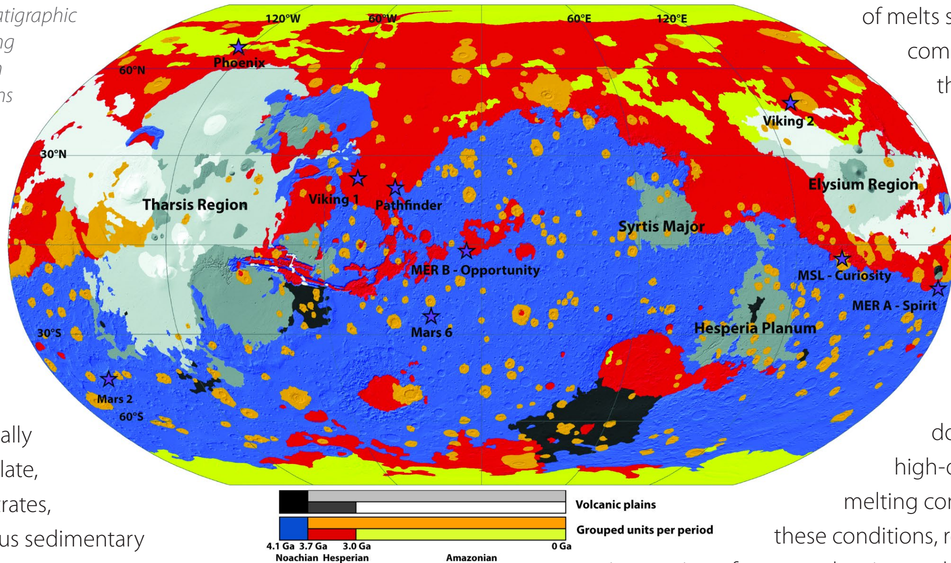


Figure 2. Chronostratigraphic map of Mars showing surfaces of common age. Volcanic terrains are subdivided separately in greyscale levels. Landing sites are highlighted with stars.

and physical characteristics are emplaced over, and potentially erode and assimilate, sulfate-rich substrates, such as the various sedimentary lithologies recently encountered at the Gale Crater and Meridiani Planum landing sites or documented from orbit.

Preliminary findings (Fig. 1) support the inference that sulfate assimilation is a potential trigger of sulfide batch segregation and consequent formation of Ni-Cu-(PGE) sulfide mineralisation. The liquidus temperature of the magma appears to be the key parameter in controlling the attainment of sulfide saturation. Therefore, only low-temperature lava flows corresponding to low-degree partial melts of the mantle are promising candidates for the presence of sulfide deposits on Mars (Fig. 2). These types of melts should be more common during the Hesperian (3.7-3.0 Ga) and especially during the Amazonian (<3.0 Ga), rather than during the Noachian, which is dominated by high-degree partial melting conditions. Given these conditions, requiring the interaction of recent volcanism and ancient sulfate-rich deposits, the window of opportunity for ore genesis on Mars may have been much tighter than on Earth, only rarely and sparsely allowing the formation of orthomagmatic mineral systems.

This project is part of CCFS Theme 1, Early Earth, and contributes to understanding Fluid Fluxes.

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Funded by: CCFS Flagship Program 4

Messengers from the deep: Fossil wadsleyite-chromite microstructures from the Mantle Transition Zone

Seismological studies of Earth's mantle reveal three distinct changes in seismic velocity, at depths of 410, 660 and 2700 km; the interval between 410 and 660 km is termed the Mantle Transition Zone (MTZ). Investigations of the MTZ by deformation experiments and geophysical methods suggest that the MTZ has distinct rheological properties. However, their exact cause is still unclear, because actual samples of mantle rocks from deeper than 200 km are rare, and we still know little about the cont...

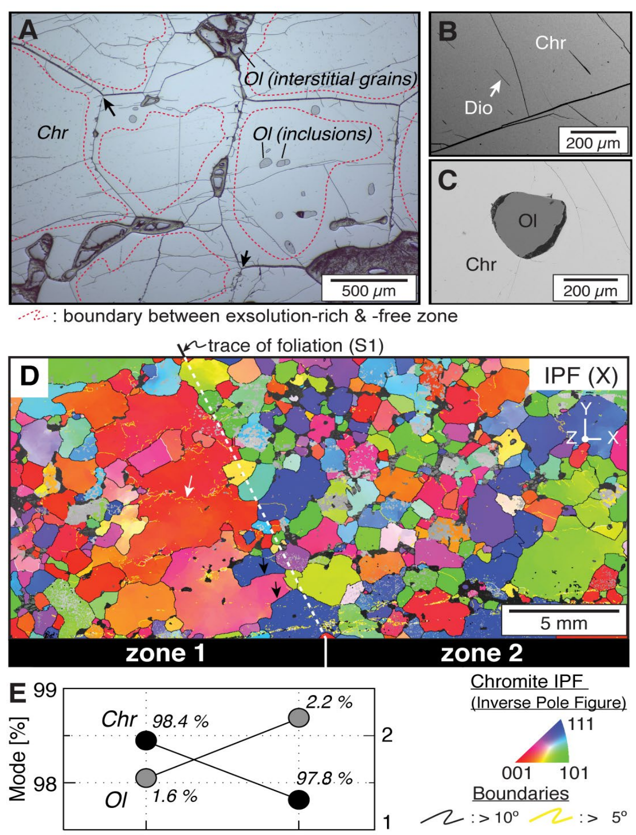


Figure 1. Microstructure of Luobusa chromitite. (A-C) Back-scattered electron (BSE). (A) Equilibrated microstructure of chromite with 120° triple junctions (black arrow) and smooth, nearly straight grain boundaries. Olivine occurs as inclusions and along grain boundaries. Interstitial grains are partially or completely serpentinised. (B) Exsolved diopside needles (Dio) in chromite (Chr). (C) Olivine inclusion (Ol) in chromite (Chr). (D) Colour coded EBSD map showing crystal orientation changes relative to the X direction of the sample reference frame. White and black arrows represent subgrain boundary and migrated grain boundary, respectively. (E) Modal composition of zone 1 and 2 in Figure 1(D).

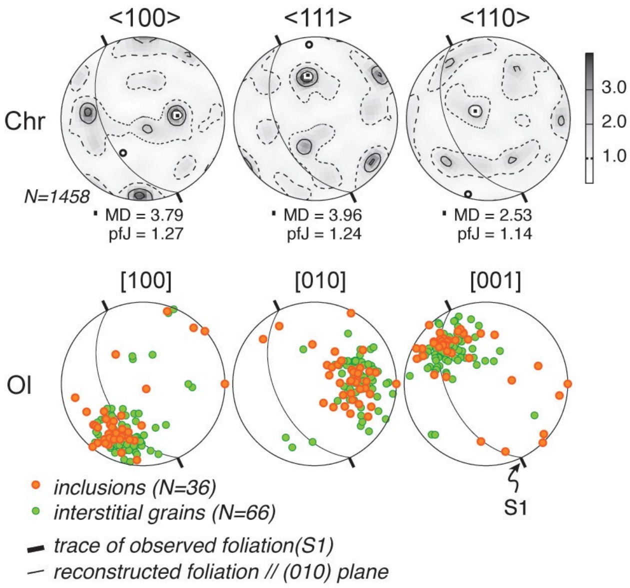


Figure 2. Crystallographic preferred orientation (CPO) of chromites (Chr) and olivines (Ol). Lower hemisphere, equal-area stereographic projections. MD: maximum density, pfJ: index of fabric intensity.

rheological properties and deformation behaviour of olivine polymorphs in the lower parts of the upper mantle.

Luobusa is one of several large peridotite massifs along the Yarlung-Zangbo suture zone of southern Tibet, which marks the boundary between the Indian and Asian blocks. The podiform chromitites in the Luobusa peridotite have received much attention because they include many ultra-high pressure (UHP) phases, such as microdiamonds (found in mineral separates and *in situ*), Si-rutile and coesite, as well as a range of highly reduced native elements, carbides and nitrides. Recently, a basic model for the subduction, MTZ UHP metamorphism and exhumation of the Tibetan peridotites has been presented (*McGowan et al., 2015, CCFS Publication #522*).

These observations indicate that the Luobusa chromitites have experienced much higher pressures than the more common ophiolitic chromitites, whose history is restricted to the uppermost part of the mantle (*González-Jiménez et al., 2014, CCFS Publication #334*).

We have discovered the first direct evidence for crystal-plastic deformation by dislocation creep in the MTZ using a chromitite from the Luobusa peridotite. Chromite grains show exsolution of diopside and SiO_2 (Fig. 1A-B), suggesting previous equilibration as an orthorhombic polymorph in the MTZ. Olivine occurs both as inclusions in chromite and interstitially along grain boundaries (Fig. 1C). The grain-size difference between the enclosed and interstitial olivine grains is consistent with evidence for grain boundary migration, because grain boundaries can readily migrate across small grains but can be pinned by larger grains. A decrease in the rate of grain growth due to the presence of grains of a second phase also is consistent with the finer grain size and higher abundance of olivine in interior zone 2 relative to exterior zone 1 (Fig. 1D-E). The abundance of exsolved diopside needles in the cores of chromite grains, vs their absence in the rims, indicates that grain growth occurred after the transition from the orthorhombic high-pressure polymorph chromite to cubic chromite.

Electron backscattered diffraction (EBSD) analysis reveals that olivine grains co-existing with exsolved phases inside chromite grains and occurring on chromite grain boundaries have a single pronounced crystallographic preferred orientation (CPO) (Fig. 2). This suggests that olivine preserves the CPO of a high-pressure polymorph (wadsleyite), which implies the activation of the (011)[100] slip system in wadsleyite, before the high-pressure polymorph of chromite began to invert and exsolve. Chromite, a cubic phase also shows a significant CPO, suggesting that this was acquired while the chromite existed in the UHP orthorhombic polymorph. Thus, the fine-grained high-pressure phases were deformed by dislocation creep in the MTZ (Fig. 3). Significant grain-boundary migration under static conditions during passive exhumation produced an equilibrated microstructure. Grain growth masked at first sight its MTZ deformation history, but preserved the core-rim structure with exsolved diopside only in the cores, as well as the high-PT fabric. The relict olivine-chromite fabric of this Luobusa chromitite provides the first direct evidence of significant crystal-plastic

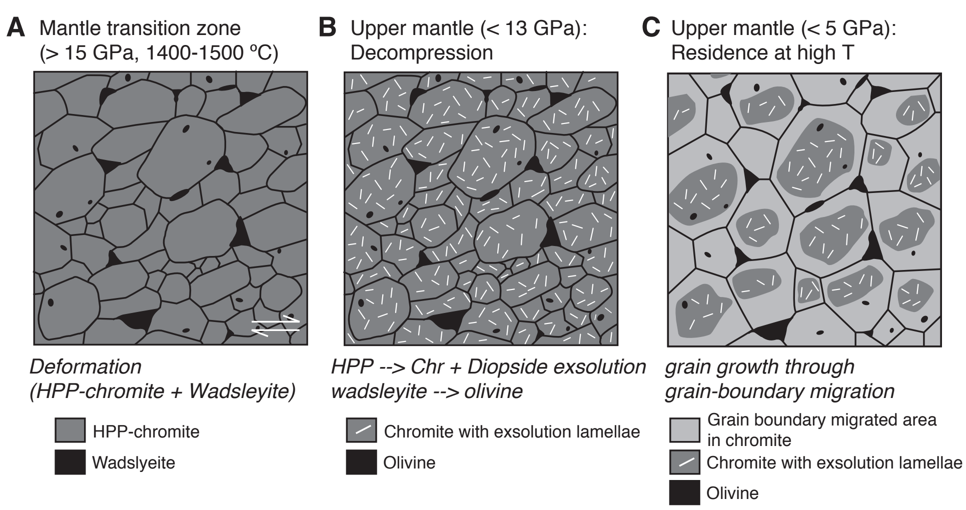


Figure 3. Schematic model of microstructural evolution in Luobusa chromitite. (A) Deformation of HPP (High Pressure Polymorph)-structured chromite and wadsleyite in Mantle Transition Zone. (B) Transformation from HPP structure to chromite; diopside/coesite exsolution; transformation of wadsleyite to olivine. (C) Grain growth through static grain-boundary migration to produce coarse equilibrated microstructure, with exsolution-rich cores and exsolution-free rims. Larger interstitial olivine grains pin the migrating boundaries.

deformation in the MTZ. These unique observations provide a window into the deep Earth, and constraints for interpreting geophysical signals and their geodynamic implications in a geologically robust context (*Satsukawa et al. 2015; CCFS Publication #673*).

This project is part of CCFS themes 2 and 3, Earth's Evolution and Earth Today, and contributes to understanding Earth's Architecture and Fluid Fluxes.

Contacts: Takako Satsukawa, Bill Griffin, Sandra Piazolo, Sue O'Reilly
Funded by: CCFS Flagship Program 1, ECSTAR

How kimberlites get to the surface (or not)

Kimberlites are economically and scientifically valuable because they are the major hosts to diamonds, entrain abundant mantle and crustal xenoliths and represent the deepest mantle-derived magmas (>150-200 km) that we can see at Earth's surface. Despite their importance, and at least 40-50 years of dedicated studies, several issues remain unresolved about kimberlite petrology, geochemistry, mineralogy and volcanology. These include: 1) the composition of kimberlite melts in the deep Earth and when they reach the upper crust; 2) the depth where kimberlite melts are generated; 3) the causes of the very fast ascent (several m/s) of kimberlite magmas; 4) the extent to which kimberlite rocks are modified by syn- and post-emplacement processes, such as ground-water alteration.

New research by ARC DECRA fellow Andrea Giuliani and his research group provides new insights into two of the above issues, namely the ascent mechanism(s) of kimberlite magmas and the evolution of kimberlite melts during their ascent through the lithospheric mantle.

The driving forces that promote the rapid ascent of kimberlite magmas are poorly constrained. For example, it has been proposed that exsolution of a CO_2-rich vapour phase at mantle depths provides the main propellant. However, this is hard to reconcile with the carbonate-rich nature of kimberlite matrices and, hence the parental magma(s); the CO_2 obviously has not escaped. In addition, many kimberlite magmas (e.g., magmatic dykes several km in length) have not been emplaced explosively. Finally, if magma ascent is not driven by volatile exsolution, we might expect the highly reactive kimberlite melts to be entirely consumed through reaction with mantle wall rocks. The ascent of kimberlite magmas to Earth's surface, therefore, requires unique conditions.

To investigate the evolution of kimberlite magmas, we need phases that preserve geochemical signatures of magma interactions during transport through the mantle and the crust. Phlogopite mica is a common mineral in kimberlites, where it spans a range in size from macrocrysts (~>0.5 mm; Fig. 1) to a groundmass phase (~<0.1 mm). It also preserves large compositional variations, a repository of information on the evolution of kimberlite and related melts.

In CCFS publication #680, Dr Giuliani and colleagues from the University of Melbourne and Tasmania, report *cont...*

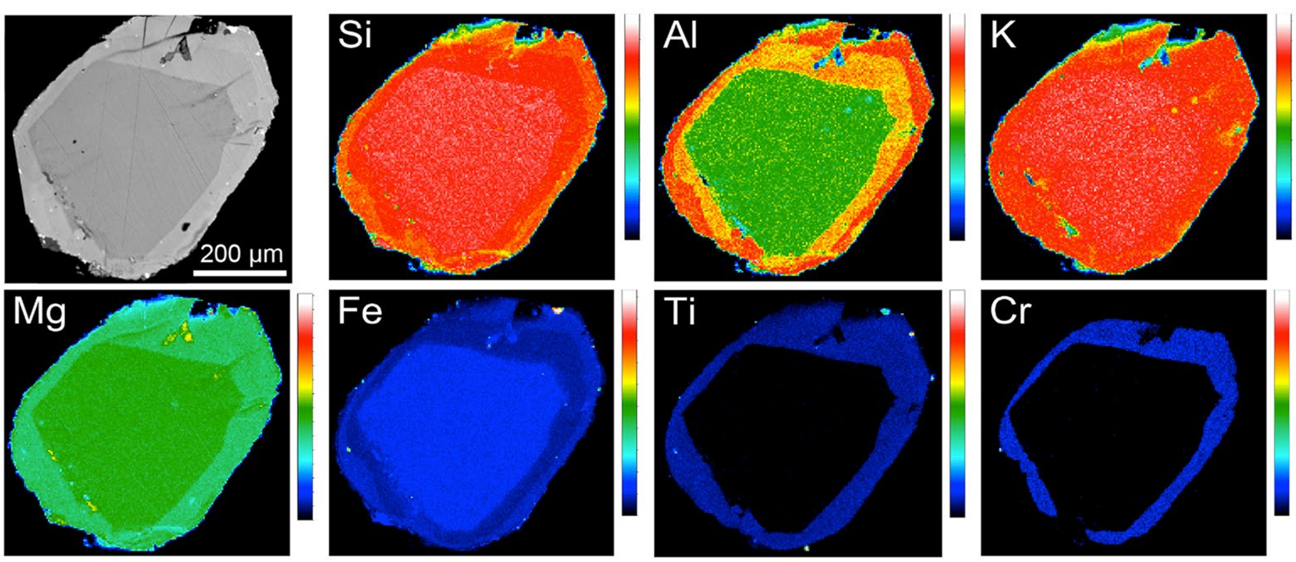


Figure 1. Scanning electron microscope (SEM), back-scattered electron (BSE) image and X-ray elemental maps of a typical concentrically-zoned phlogopite macrocryst from the Bultfontein kimberlite. The coloured scales on the right of each panel indicate the relative concentration of each element, i.e. 'cool' colours (blue, black) = low concentrations; 'warm' colours (red, orange) = high concentrations.

new compositional data for phlogopite in the Bultfontein kimberlite (Kimberley, South Africa; the kimberlite type locality) and in mantle xenoliths entrained by the Kimberley kimberlites. Concentric zoning patterns in phlogopite macrocrysts in the Bultfontein kimberlite (Fig. 1) record a complex history of episodic crystal growth. Internal zones of macrocrysts and some cores in groundmass grains have Ti-Cr-rich compositions similar to overgrowth rims on phlogopite in mantle xenoliths from the Kimberley and other southern African kimberlites and matrix grains in polymict breccia xenoliths from Bultfontein. In mantle xenoliths, the phlogopite overgrowths have been previously interpreted as crystallising from kimberlitic fluids/melts, while polymict breccias are widely regarded as failed kimberlite intrusions at mantle depths. These results suggest that the Ti-Cr-rich zones of phlogopite in the Bultfontein kimberlite were produced in the mantle by reaction with one or more batches of kimberlite melt before phlogopite entrainment into the magma and transport towards the Earth's surface. Similar Ti-Cr-rich phlogopite cores were also identified in the groundmass of kimberlites from North America. Inner rims in phlogopite macrocrysts from the Aries kimberlites/orangeites and olivine macrocrysts and groundmass grains from kimberlites in Greenland, Canada, southern Africa and Russia have also been attributed to kimberlite metasomatism in the mantle.

This evidence, coupled with the occurrence of polymict-breccia xenoliths in South African and Russian kimberlites, indicates that '*failed*' kimberlite intrusions are probably a common phenomenon. Given the highly reactive nature of kimberlite melts towards mantle wall rocks, kimberlite magmas may only be able to reach the surface by ascent through a pathway created by multiple earlier magma pulses that metasomatise the conduit, insulating the later magmas from reaction with the surrounding mantle rocks (Fig. 2). This model might represent the fundamental ascent mechanism for kimberlite magmas.

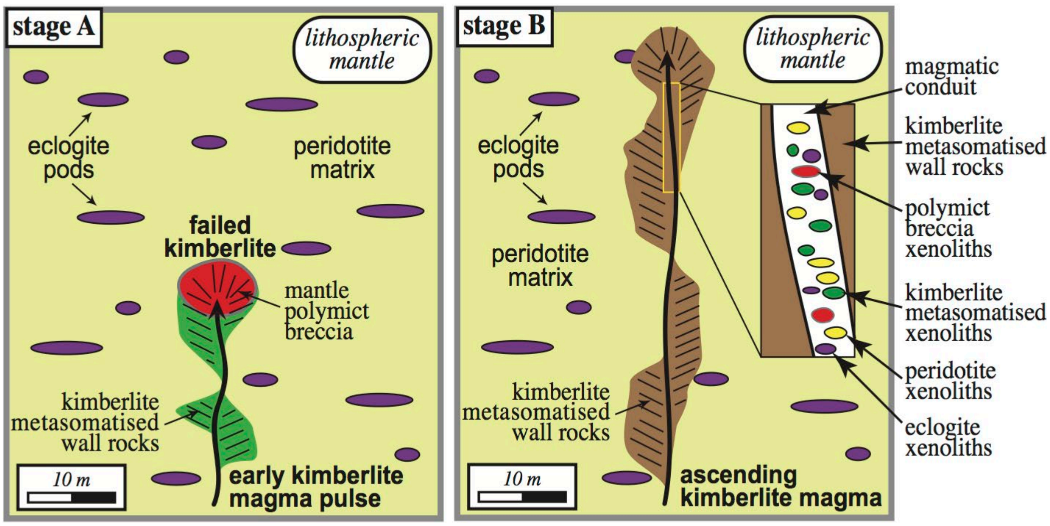


Figure 2. Conceptual model showing different stages in the evolution of a kimberlite magmatic system traversing the lithospheric mantle. Stage A: 'failed' kimberlite intrusion stalled at lithospheric mantle depths with the formation of polymict breccias and metasomatism of the conduit wall rocks. Stage B: the ascending kimberlite magma intrudes the pre-existing conduit and entrains wall rocks, including polymict breccias and previously metasomatised components (i.e. macrocrysts). The patchy occurrence of 'kimberlite-metasomatised wall rocks' illustrates that not all material entrained and transported to the surface is metasomatised, in agreement with the occurrence of abundant peridotite and eclogite xenoliths, that show minimal evidence of metasomatism by kimberlite magmas or related fluids. Other possible reasons for the abundance of non-metasomatised wall rocks include sampling of rocks several metres away from the metasomatised conduit, which could be incorporated into the conduit during the turbulent ascent of the larger kimberlite magma pulses and preferential melting and disaggregation of metasomatised wall rocks during kimberlite magmatic activity. The scale is based on a typical thickness of kimberlite dykes of about 0.5-1 m.

This study has also revealed that, in addition to the widely recognised magmatic and xenolithic components, kimberlite rocks host mantle-derived '*antecrysts*' (e.g., the high Ti-Cr zones of phlogopite grains), which are the products of '*failed*' kimberlite intrusions and were entrained by later kimberlite magmas. Mantle-derived antecrysts are an integral part of the kimberlite groundmass, where they occur as cores in groundmass grains. These antecrysts contribute to the bulk composition of kimberlites, and further complicate efforts to determine the composition of parental kimberlite melts by bulk-rock analysis.

This project is part of CCFS Theme 2, Earth's Evolution, and contributes to understanding Earth's Architecture and Fluid Fluxes.

Contact: Andrea Giuliani

Funded by: ARC Discovery Early Career Researcher Award (DECRA)

A new zircon guide to copper-fertile igneous intrusions

The hunt for undiscovered mineral resources in igneous bedrock is increasingly reliant on *'halos'* - signals around an ore deposit that are much larger than the ore deposit itself. Stream sediments shed during erosion of an ore-bearing igneous complex can provide such a halo and can serve as guides to undiscovered ore upstream from the sediment sampling site.

CCFS research has identified several geochemical discriminants of granitic igneous rocks that produced magmatic-hydrothermal copper deposits. This type of deposit accounts for more than 75% of global copper production (*R. Loucks, Australian Journal of Earth Science, 2014*). Among the geochemical discriminants is the ratio europium/ytterbium, represented by the parameter (Eu/Eu*)/Yb. Eu/Eu* represents the *'Europium anomaly'* - the deviation of the measured abundance (Eu) from the abundance expected from the measured amounts of samarium and gadolinium (Eu*), which have atomic numbers just below and above, respectively, that of europium. Granitoid melts related to copper ores are distinguished from barren granitoid melts by unusually high values of Eu/Eu* and unusually low values of Y; the ratio (Eu/Eu*)/Yb magnifies the distinction of copper-ore-forming granitoid magmas from barren granitoid magmas.

Zircon, a ubiquitous trace mineral in granitic igneous rocks, takes in small amounts of Eu and Yb that substitute for some of the zirconium atoms in the zircon structure. We have discovered that zircon inherits a version of the (Eu/Eu*)/Yb ratio in its parent granitoid melt, warped by zircon's systematic preference for Yb relative to Eu. Europium atoms in the silicate melt can have an electric charge of +2 or +3; the granitoid melt's ratio of Eu^{2+}/Eu^{3+} is captured in the quantity Eu/Eu*. Zircon inherits a version of the parent granitoid melt's Eu/Eu*, warped by zircon's strong preference for Eu^{3+} relative to Eu^{2+}. Zircon also takes in small amounts of the elements cerium (Ce) and neodymium (Nd); magmas related to copper ores have unusually low abundances of Y, and zircon that crystallises from Y-depleted magmas inherits that feature as well. Finally, zircons from copper-ore-forming granitoid magmas have distinctively high values of the ratio Ce/Nd, as compared to zircons from barren granitoids. The ratio (Ce/Nd)/Y in zircon thus magnifies the distinction between zircons from mineralised and unmineralised granitoid rocks.

We have measured (Eu/Eu*)/Yb and (Ce/Nd)/Y in hundreds of zircons from four major magmatic-hydrothermal ore deposits and nine barren igneous complexes, and compiled from the literature more than 2500 analyses of zircons from other copper-ore-bearing and barren igneous complexes. Figure 1 illustrates the efficacy of these parameters in discriminating zircons in copper-ore-bearing igneous complexes from zircons in barren reference suites. Because zircon is chemically and mechanically robust, it survives chemical alteration of its host rock and long-distance transport in streams. Our discovery allows the trace-element chemistry of zircon to be used by mineral exploration companies as a pathfinder to copper-fertile igneous complexes that may contain undiscovered ore. The analytical method used in our study, laser-ablation inductively-coupled plasma mass spectrometry, can do hundreds of analyses per day at a price that is cost-effective for mineral exploration.

This project is part of CCFS Themes 2 and 3, Earth's Evolution and Earth Today and contributes to understanding Fluid Fluxes.

Contacts: Robert Loucks, Yongjun Lu, Marco Fiorentini

Funded by: CCFS Flagship Program 2

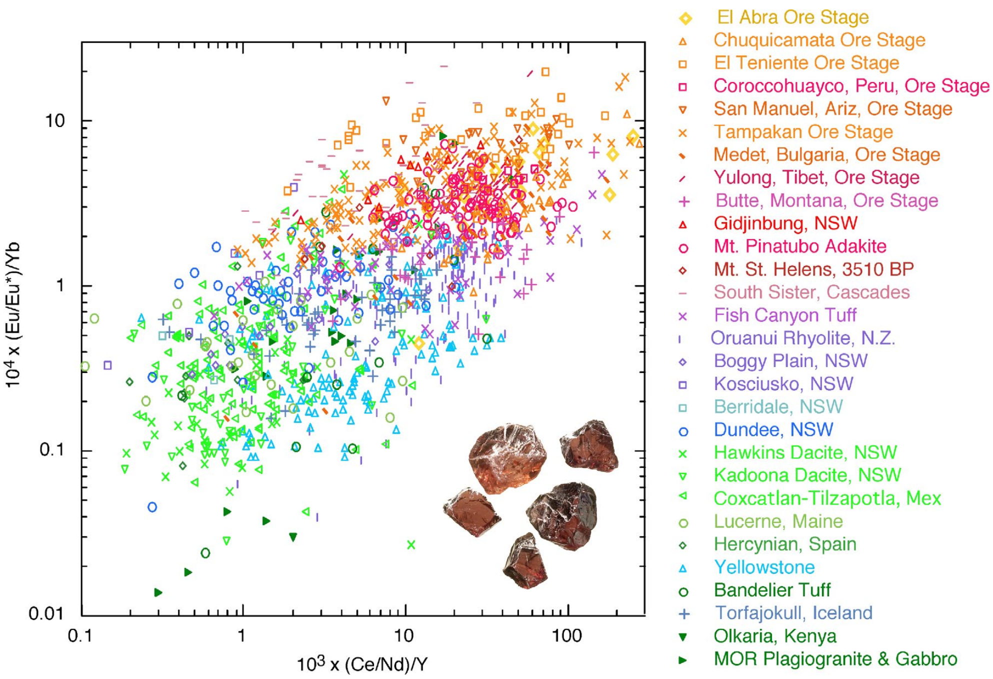
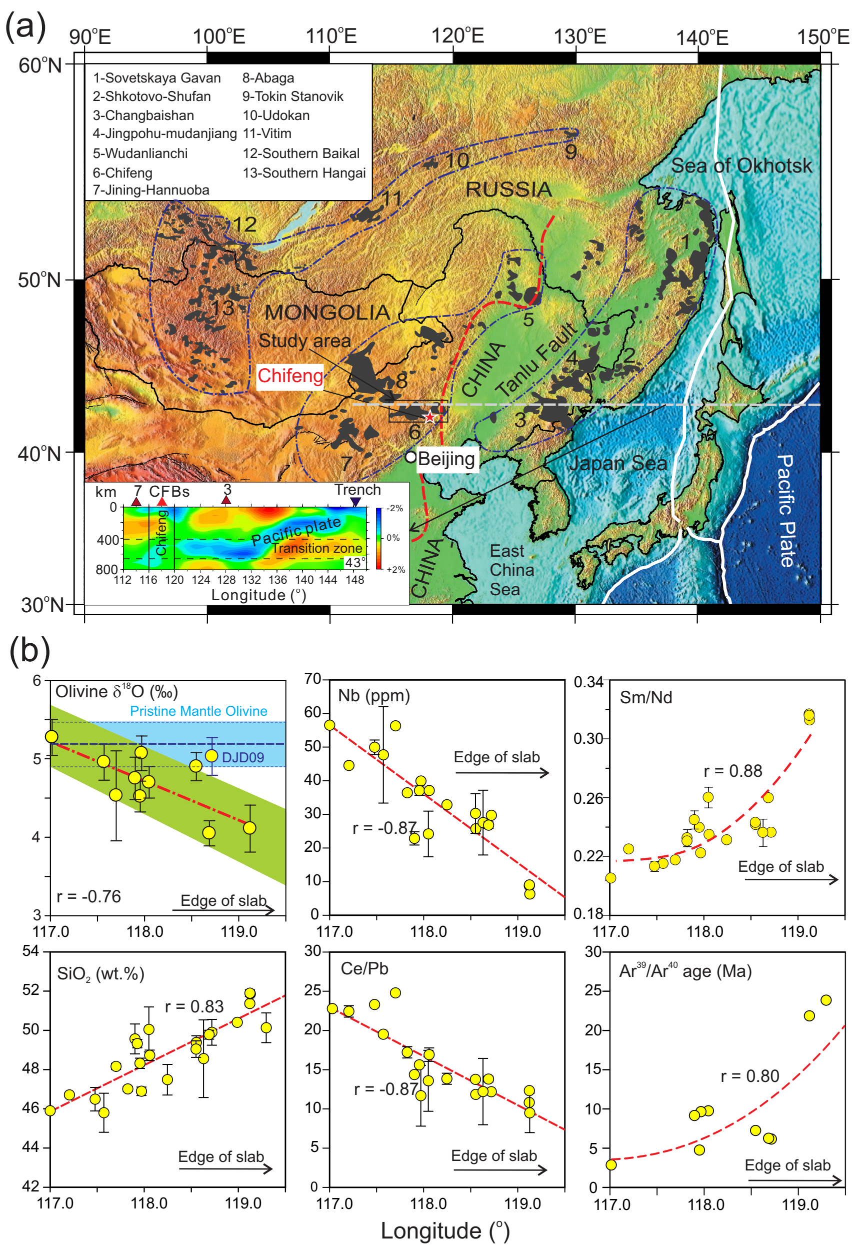


Figure 1. Trace elements in more than 3000 zircon crystals from copper-ore-bearing igneous complexes (red and orange symbols) and from unmineralised igneous complexes (violet, blue, green symbols). Because zircon robustly survives chemical alteration of its host rock and long-distance sedimentary transport, zircons in sediments can guide mineral exploration teams to copper-mineralised igneous complexes upstream from the sediment-sampling site.

Do continental flood basalts need plumes?

It has previously been postulated that the Earth's hydrous mantle transition zone may play a key role in intra-plate magmatism, but no confirmatory evidence has been reported. Here, we argue that high-temperature hydrothermally-altered subducted oceanic crust was involved in generating the Late Cenozoic Chifeng continental flood basalts of East Asia. This study combines oxygen isotopes with conventional geochemistry to provide the first evidence for an origin in the hydrous mantle transition zone.

The most striking observation in this study is that oxygen isotopes, $^{39}Ar/^{40}Ar$ ages, and other geochemical features of the Chifeng CFBs (SiO_2, Nb, Sm/Nd, and Ce/Pb) are correlated with their distance from the western edge of the stagnant Pacific slab (Fig. 1). In a westward direction, the lavas decrease in age, become progressively depleted in silica and have lower Sm/Nd ratios, whereas they show progressive enrichment in Nb and have higher Ce/Pb ratios. Importantly, the $\delta^{18}O$ values of olivine in the basalts increase westward away from the stagnant slab (Fig. 1). Thus the lavas immediately above the western edge of the stagnant Pacific slab are over-saturated in silica, and have the oldest eruptive ages, the lowest olivine $\delta^{18}O$ and possibly the highest fluid contents. The low-$\delta^{18}O$ lavas are characterised by enrichment of silica, high positive Sr anomalies, high Al_2O_3, and depletion in incompatible trace elements (Fig. 2), and Ce/Pb ratios like those commonly associated with subducted slabs (Fig. 3). Furthermore, the lower $\delta^{18}O$ is coupled with depletion in high field-strength elements (e.g., Nb; Fig. 2) and other incompatible elements, as evidenced by decreasing La/Sm ratios.



This is confirmed by the studies of olivine-hosted melt inclusions from the south-eastern extremity of the Chifeng CFBs, erupted directly above the western edge of the stagnant Pacific slab. The melt-inclusion data imply that these CFBs were mainly derived from an olivine-free pyroxenite-dominated source with high water content (>450 ppm). These observations show that the low-$\delta^{18}O$ end-member melts most likely originated from hydrothermally-altered oceanic gabbros. Thus, the correlation of recycled oceanic gabbro-derived signatures with the inferred position of the stagnant Pacific slab within the hydrous MTZ provides an indirect, but important, constraint on the depth of the mantle source.

These observations lead us to propose an alternative model, whereby slab-triggered wet upwelling produces large volumes of melt that may rise from the hydrous mantle transition zone. This model explains the lack of pre-magmatic lithospheric extension or a hot-spot track

Figure 1. (a) Schematic map of the Late Cenozoic intraplate volcanic province in Central East Asia. (b) Covariations of olivine $\delta^{18}O$, major-trace elements, and $^{39}Ar/^{40}Ar$ ages as a function of eruptive longitude (for detail see text in X.C. Wang et al., 2015, Nature Communications, 6). Data points represent average of analysed whole-rock or olivine samples from individual Chifeng CFBs; error bars represent one standard deviation for each group of lava or olivine. r: correlation coefficient

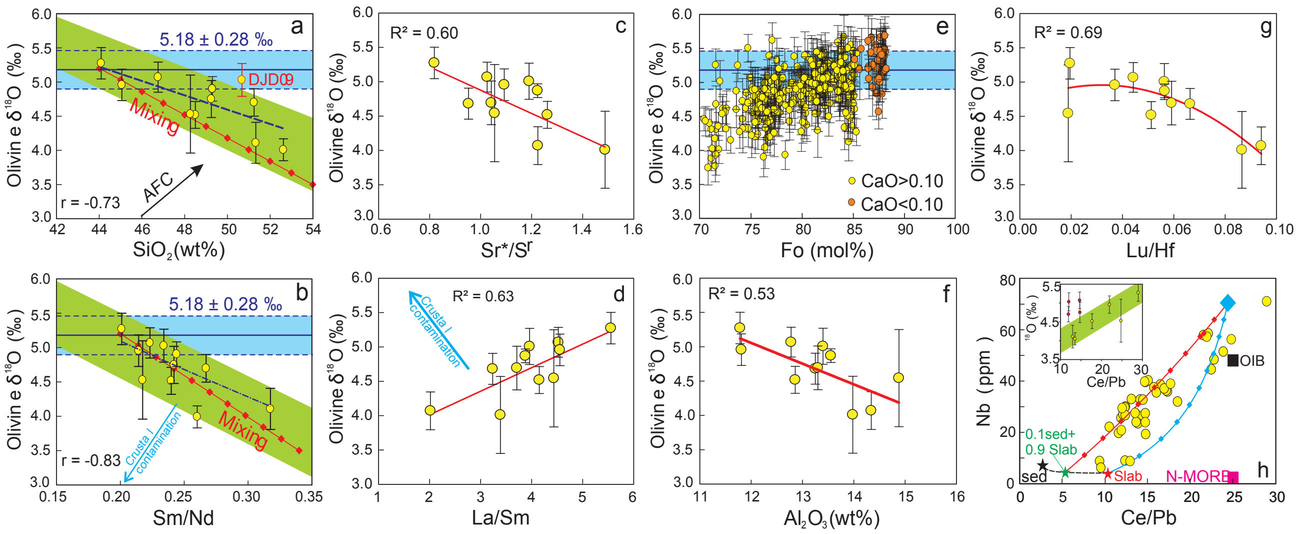


Figure 2. Correlation between average oxygen δ18O values and (a) SiO_2, (b) Sm/Nd, (c) Sr/Sr, (d) La/Sm, (e) Fo contents, and (g) Al_2O_3, and (h) Lu/Hf and (f) Nb-Ce/Pb.*

and also the arc-like signatures observed in some large-scale intra-continental magmas. Deep-Earth water cycling, linked to cold subduction, slab stagnation, wet mantle upwelling, and assembly/breakup of supercontinents, can account for the chemical diversity of many continental flood basalts (Fig. 3).

This project is part of CCFS Theme 2, Earth's Evolution, and contributes to understanding Earth's Architecture and Fluid Fluxes.

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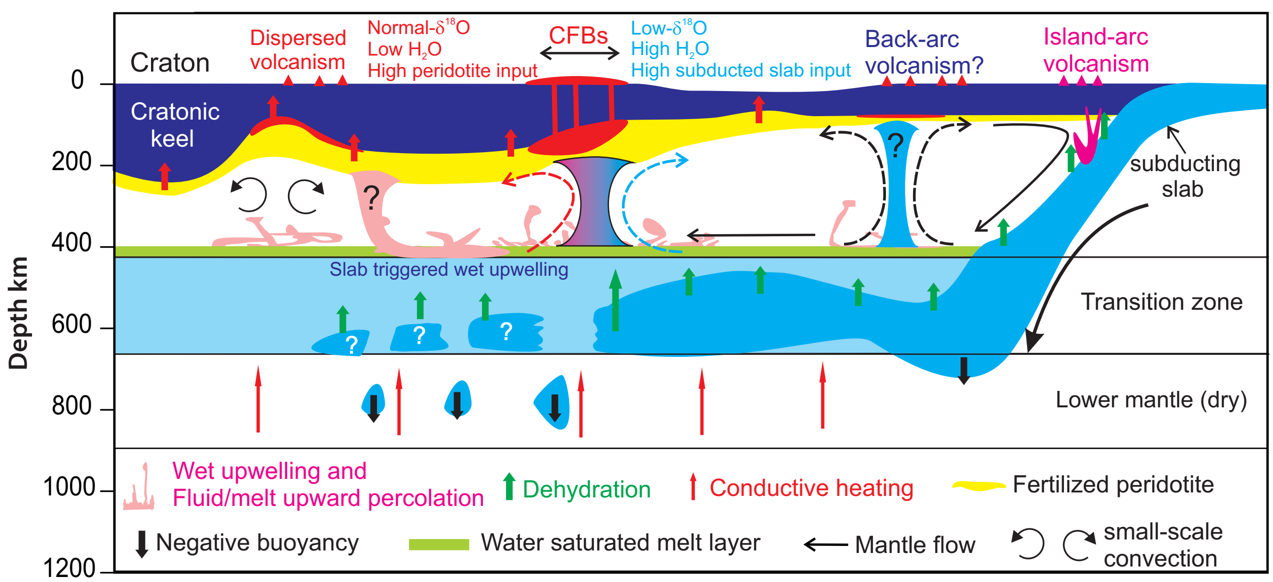


Figure 3. Effect of slab stagnation and water cycling (wet upwelling, upward percolation, and re-fertilisation) on the upper mantle thermochemical state. This model is mainly based on the strong spatial correlation of geochemical features with distance of eruptive lavas relative to the edge of the stagnant slab. It involves water partitioning in the Earth's mantle, behaviour of slab-triggered wet upwelling and upward percolation, hydrous mantle melting, the mantle wedge model, and upwelling from the hydrated mantle transition zone.

Ancient mantle lithosphere beneath the Khanka massif in Russian Far East: *In situ* Re-Os evidence

The Altaids (or Central Asian Orogenic Belt; CAOB) has been proposed as the world's largest site of juvenile crust formation during the Phanerozoic eon. Nevertheless, Kröner et al. (2014) documented that crustal evolution in the CAOB involved both addition of juvenile material from the mantle as well as abundant reworking of varying proportions of older crust throughout its

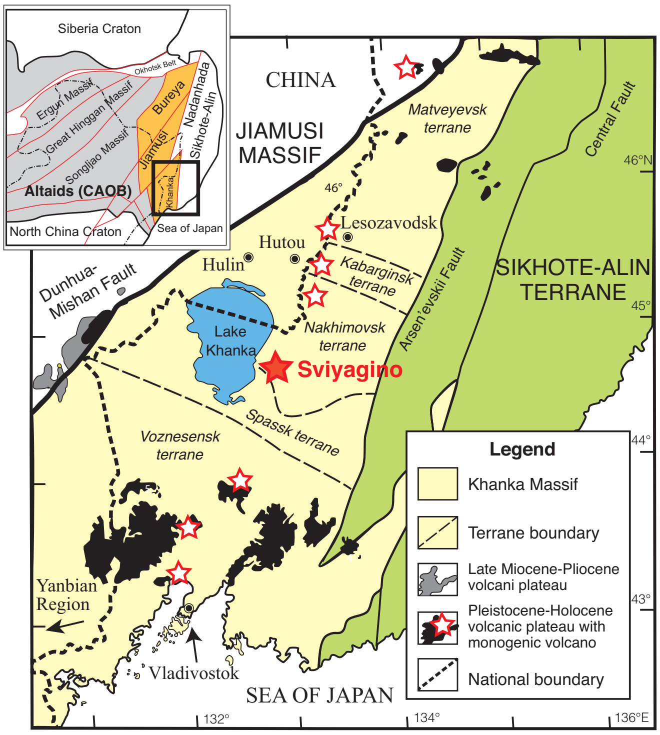


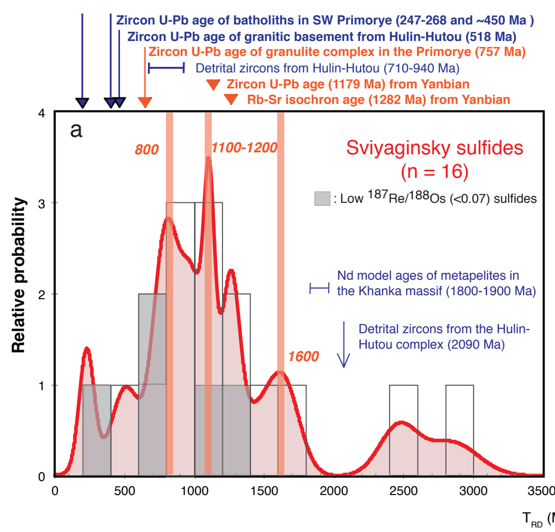
Figure 1. Tectonomagmatic map of the Khanka massif in relation to adjacent areas of NE China and Russia. Red stars: localities of individual volcanic domes; solid red star: locality of xenoliths from the Sviyaginsky volcano.

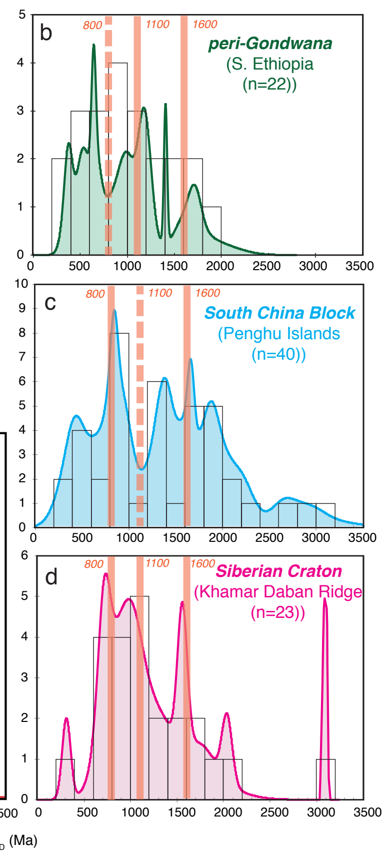
accretionary history. Within the CAOB, several microcontinental blocks have been recognised, although it is still unclear if all of these truly predated accretion of the CAOB. This is also the case for the extreme eastern margin of the CAOB, which is composed of three microcontinental blocks: the Bureya, Jiamusi and Khanka massifs, located between the Siberia and North China cratons; the ongoing Pacific-plate subduction since the Mesozoic complicates the situation (Fig. 1).

Lack of constraints has led to widely divergent views as to the origin and initial location of these blocks. It has been postulated that the Jiamusi-Khanka massif may be derived from a peri-Gondwana position, or be an exotic block of affinity to South China Block, or a fragment of the Siberian Craton.

Recent studies have demonstrated that Os model-age spectra from mantle xenoliths commonly show age peaks corresponding to the ages of thermal/tectonic events in the overlying crust. Thus, *in situ* analysis of Re-Os isotopic compositions by laser sampling of single sulfide grains makes it possible to test the existence of a Precambrian microcontinent within the eastern CAOB complex and clarify whether the Khanka massif has a tectonic affinity to the Siberian Craton. The Os isotope compositions of sulfides in mantle xenoliths hosted by late Miocene alkali basalts from the Sviyaginsky volcano, Russian Far East (Fig. 1), reveal the presence of Archean-Proterozoic subcontinental lithospheric mantle (SCLM) beneath the Khanka massif. Both their T_{MA} and T_{RD} model ages reveal similar peaks at 1.1 and 0.8 Ga suggesting later thermotectonic events in the SCLM, whereas T_{RD} model ages extend back to 2.8 ± 0.5 (2σ) Ga. The events recognised in the SCLM are consistent with those recorded in crust of the Khanka massif. The sulfide

Figure 2. Cumulative probability diagrams (Ludwig, 2000) of T_{RD} model ages of sulfides from (a) the Sviyaginsky volcano; (b) the Turkana Depression in south Ethiopia on the Arabian-Nubian Shield (Wang et al., 2005); (c) the Penghu Islands in Taiwan at the margin of the South China Block (Wang et al., 2003, 2009a); and (d) the Khamar Daban Ridge in south Russian Siberia on the Slyudyansky terrane (our unpublished data). Thick line represents the distribution pattern of ages. The histogram of ages represented by thin grey lines is also shown. Grey bars indicate sulfides with low $^{187}Re/^{188}Os$ ratios (<0.07) having pristine characteristics without later modification. Corresponding crustal events are shown for comparison.





Os-isotope data show that the SCLM beneath the Khanka massif had formed at least by the Mesoproterozoic, and probably in the Archean, and was subsequently metasomatised during juvenile crustal-growth events related to the evolution of the Altaids. The peak Os model age pattern of the Sviyaginsky sulfides, compared to sulfide Os model ages from these terrains, provide further insights on the origin of the Khanka massif. In Figure 2, peak Os model age patterns of sulfides in mantle xenoliths from Turkana Depression in south Ethiopia on the Arabian-Nubian Shield (*Wang et al., 2005*), the Penghu Islands at the margin of South China Block (*Wang et al., 2003; 2009*), and the Khamar Daban Ridge in south Russian Siberia (Slyudyansky terrane; our unpublished data) are shown for comparison with the Sviyaginsky sulfides. Sulfides from south Ethiopia (Fig. 2b) do not have the Mesoproterozoic-Archean Os age record, and their peak Os age patterns are not consistent with the Sviyaginsky sulfides. The Sviyaginsky sulfides have pronounced peak ages at 1.1-1.2 and 0.8 Ga, while the Taiwan sulfides obviously do not have an age peak at 1.1-1.2 Ga (Fig. 2c). Only sulfides from the Slyudyansky terrane have peak age patterns similar to the Sviyaginsky sulfides (Fig. 2d). Thus the Khanka massif has tectonic affinities to the Siberian Craton and probably was derived from it, as proposed by Zhou et al. (2010).

This project is part of CCFS themes 1 and 2, Early Earth and Earth's Evolution, and contributes to understanding Earth's Architecture and Fluid Fluxes.

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Funded by: Ministry of Science and Technology, Taiwan projects NSC 101-2923-M-001-001-MY3, NSC99-2116-M-001-017

Palaeoproterozoic Superia Supercraton: New insights from Yilgarn

The hypothesis of supercontinent cycles predicts the assembly of a supercontinent in Siderian time (2.5-2.3 Ga). Bleeker and Ernst (Dike swarms 2006) postulated the existence of the Superia supercraton at that time, which included the Superior, Karelia and Hearne cratons. Söderlund et al. (Precambrian Research 2010) provided some evidence that the Zimbabwe and Yilgarn cratons could also have formed part of Superia. To test this hypothesis we studied the Erayinia mafic dykes in the eastern part of the Yilgarn Craton. This study has been done in collaboration with Bert De Waele (SRK Consulting), Sarah Jones (St Barbara Limited), Ulf Söderlund (Lund University) and Richard Ernst (Carleton University) (*CCFS publication #508*).

Previously undated Erayinia dykes have been thought to belong either in the 2.42-2.41 Ga Widgiemooltha LIP or in the 1.21 Ga Marnda Moorn LIP. We dated Erayinia dykes at 2401 ± 1 Ma (U-Pb TIMS baddeleyite). The palaeomagnetic analysis isolated a stable primary remanence with steep downward direction similar, but not identical to that of the previously studied Widgiemooltha dykes. This slight directional difference and the opposite palaeomagnetic polarity suggest that Eryiania dykes are probably not related to the 10 m.y. older Widgiemooltha LIP. The comparison of Eryiania and Widgiemooltha palaeopoles suggest the angular velocity of the Yilgarn Craton between 2410-2420 and 2400 Ma at ~1°/m.y., which is comparable with similar estimations for the angular plate velocities in the Phanerozoic. The estimated amplitude of the geomagnetic secular variations at c. 2400 Ma is slightly higher than predicted by the existing models for the last 5 m.y. at the c. 64°latitude.

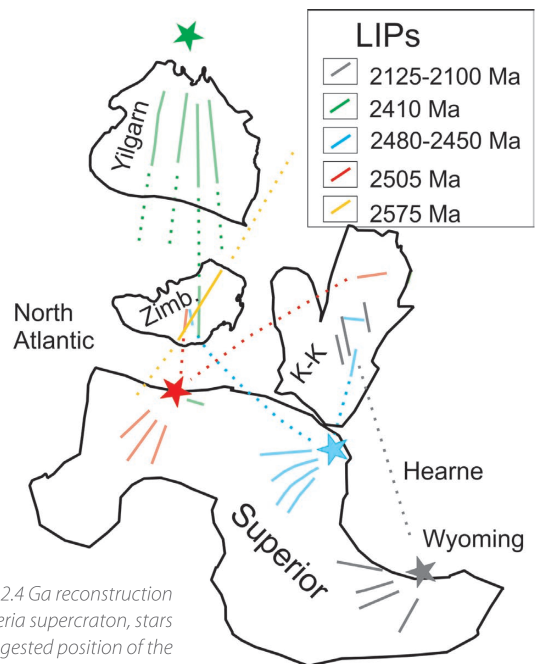

Figure 1. 2.4 Ga reconstruction of the Superia supercraton, stars denote suggested position of the mantle plumes.

New palaeomagnetic poles, together with previously published palaeopoles and with the analysis of Palaeoproterozoic LIPs distribution, led us to a modified reconstruction of the Superia supercraton at c. 2.4 Ga (Fig. 1) and confirmed the suggestion that the Superior, Yilgarn, Zimbabwe, Kola-Karelia, North Atlantic, Hearne and Wyoming cratons could be parts of this supercraton.

This project is part of CCFS themes 1 and 2, Early Earth and Earth's Evolution, and contributes to understanding Earth's Architecture.

Contact: Sergei Pisarevsky
Funded by: CCFS Flagship Program 5, LIPs - Supercontinent Reconstruction - Resource Exploration Project (www.supercontinent.org)

3D Magma emplacement

Magma generation and emplacement is an important process of material transfer that shapes much of Earth's continental crust. Molten material generated below the lithosphere contributes to the growth of the continental crust, erupting as magmas in near-surface regions or large growing magma bodies at sub-crustal levels. Understanding the physical processes involved in the generation and emplacement of magma requires knowledge about the geochemical and physical properties of melt, magma (melt plus crystals) and host lithologies. Different magma sources, melting conditions and differentiation processes have been proposed to account for the basaltic and andesitic magmatism that operates on Earth's surface. However, it is becoming increasingly apparent that the evolution of magmas is intrinsically related to transport mechanisms, which control emplacement depths, structures and petrogenesis. Transport mechanisms that have been proposed in the past can be divided into two main groups, processes of diapiric-like emplacement and those that favour magma ascent in dikes. However, it seems that nature combines both processes, which may simultaneously or sequentially control ascent and emplacement. On the other hand, crustal heterogeneities, rheological anisotropy and local and far-field stresses are likely to play key roles in magma emplacement. Feedback between these processes will affect how and where magma is stored.

Despite the rapidly growing volume of geological, geophysical and experimental data on magma rheology, chemistry, structure and emplacement, numerical simulations on the dynamics of magma ascent and emplacement are comparatively rare. Numerical studies devoted to magmatism have instead mainly focused on the internal dynamics of magma chambers, and little is known about the visco-brittle/plastic interplay between magma and crust.

The new set of 3D numerical experiments demonstrates the first-order importance of host rock rheology upon emplacement; it is responsible for the variable shapes of the intrusions, such as cone shaped, saucer shaped, funnel shaped and tabular. Brittle parameters such as cohesion and friction angle, and especially the strain limit for fracture-related weakening are important. For example, with a fully mafic crust and strain hardening, the shape of the intrusion and the surrounding faults imitate the shapes of magmatic bodies observed in nature, such as '*ring complexes*' (Fig. 1a), which are incredible magmatic structures, and a rich source of information on magma transport and emplacement. On the other hand, with strain weakening the intrusion travels very rapidly through the crust and is of relatively small diameter without much deformation of the host rock.

This study also allows a glimpse into a long-standing debate on how and if magmas are controlled by extensional regimes or pre-existing shear zones (Fig. 1b).

It has been confirmed that pre-existing faults or shear zones control the development of the shape of the intrusion. Interestingly this control is better observed with mafic host rocks than with felsic rocks. In the first instance the shape of the intrusion strictly follows the pre-exisiting zones of weakness and flat dykes can be observed (Fig. 1b). On the other hand the boundaries of intrusions into felsic host-rocks do not sharply follow the pre-existing weak zones.

This project is part of CCFS Theme 2, Earth's Evolution, and contributes to understanding Earth's Architecture and Fluid Fluxes.

Contact: Weronika Gorczyk

Funded by: ARC Linkage Project, CCFS Flagship Program 2

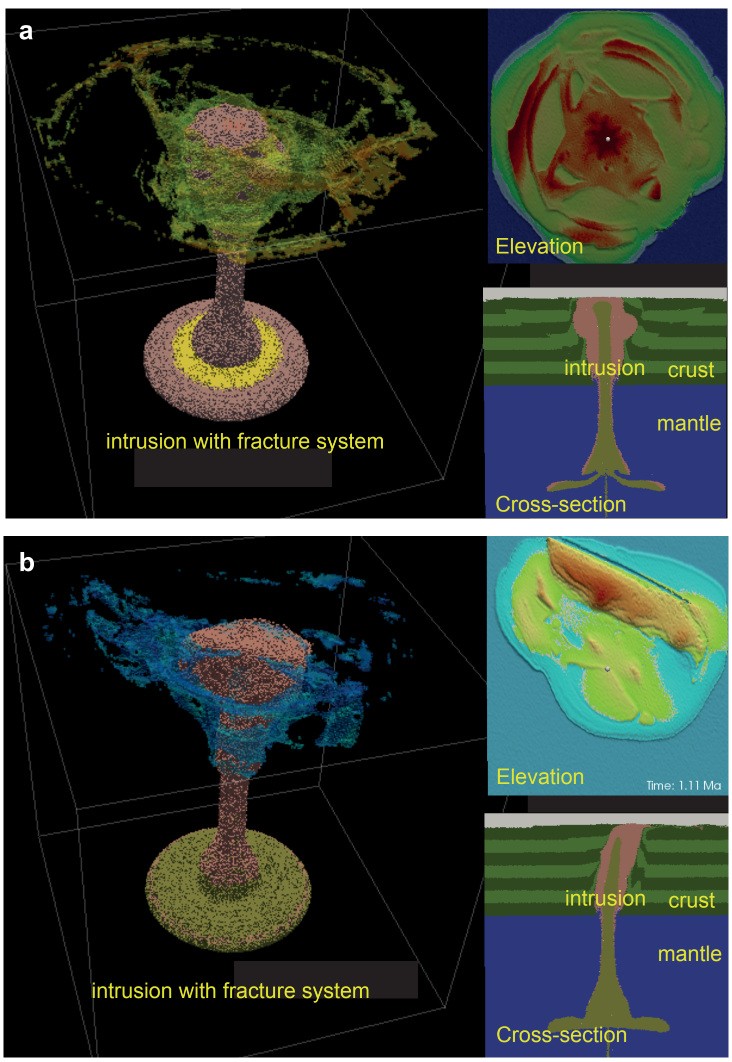

Figure 1. 3D image represents an intrusion and the fracture system that develops around it. a) simulating a ring complex. b) simulating the directionality of the intrusion with a pre-existing weak structure, such as a fault. Top right (a, b): relative elevation: blue <0, red - >0, green = 0. Bottom right (a, b): cross-section through the middle of the intrusion showing rock composition.

Solving the "Ophiolite Conundrum"

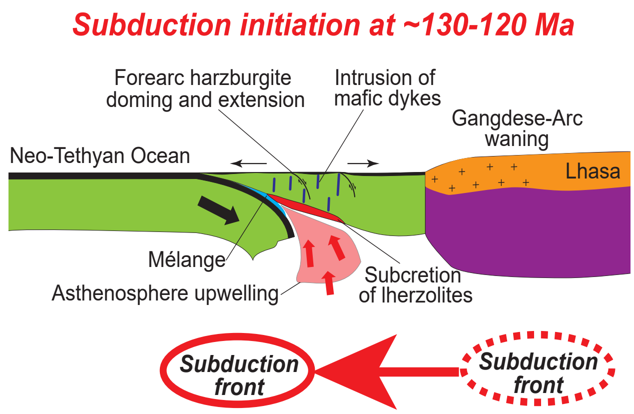

Figure 1. Cartoon illustrating the southward jump of the Neo-Tethyan subduction front at ~130-120 Ma, resulting in the subduction initiation and forearc lithosphere accretion as future Yarlung Zangbo ophiolites in South Tibet, China.

Ophiolites record shallow plate-tectonic processes in oceanic basins, arcs and ocean-continent transitions on Earth; recent confirmation of natural ultrahigh-pressure and super-reduced phases (e.g., diamond, moissanite) from Tibetan ophiolites shows that these pieces of ancient lithospheric fragments can also provide new insights into the deep convective mantle and even the Transition Zone (410-660 km). However, a long-term global conundrum (supra-subduction-zone-type ophiolites with mid-ocean-ridge features) impedes further understanding of ophiolite formation and relevant geodynamic processes. We have carried out a systematic petrological and geochemical investigation of the Zedang ophiolite (outcrop area ~100 km_2) in the Yarlung Zangbo Suture Zone (South Tibet, China), which marks a tectonic boundary between the Indian and Asian continents.

In the Zedang ophiolite, detailed mineral chemical data reveal a two-layered lithospheric mantle structure: the harzburgite domain in the east [spinel Cr# (mole $Cr^{3+}/(Cr^{3+}+Al^{3+})$ = 0.62-0.33] is more depleted than the lherzolite domain in the west (spinel Cr# = 0.30-0.17) and shows much lower equilibration temperatures (differences of ~250-150 K) than the lherzolites. Clinopyroxene trace-element compositions indicate that the harzburgites underwent pervasive metasomatism after melt extraction, while the lherzolites did not.

New zircon U-Pb ages show that the harzburgites were intruded by dolerite dykes with clear chilled margins at ~130-128 Ma, consistent with the widespread but minor mafic magmatism at ~130-120 Ma in the Yarlung Zangbo ophiolites. Nd-Hf isotopic data indicate that the Zedang lherzolites subcreted the pre-emplaced harzburgites concurrently with the intrusion of the dolerite dykes into the harzburgites, and that the lherzolites and dolerites both were derived from upwelling asthenosphere with minor slab input. Furthermore, available zircon geochronology and Hf-isotope data show that juvenile magmatism in the northern Gangdese Arc (southern part of the Lhasa microcontinent) almost ceased from ~130-120 Ma. These observations suggest a southward jump of the Neo-Tethyan subduction front from beneath the Gangdese subarc region (north) to the forearc oceanic lithosphere (south) during this short period. This jump may have been triggered by plate reorganisation related to the collision between the Lhasa cont...

Figure 2. Kang Wu, Xiaoxiao Huang, Qing Xiong and Xiaohan Gong climbing the Dazhuka Mountain, Xigaze ophiolite (S. Tibet).

and Qiangtang blocks, and the Gondwanaland breakup in the early Cretaceous.

We find that the relocation of the Tethyan subduction front caused the subduction initiation in front of the southern margin of the Gangdese Arc at ~130-120 Ma, and consequently resulted in asthenosphere upwelling, subcretion of lherzolites, doming and extension of the overlying harzburgitic forearc lithosphere and the intrusion of mafic dykes (Fig. 1). The extensional structure and MORB-type magmatism are similar to those usually observed in slow-spreading mid-ocean-ridges, and can be easily interpreted as formed during subduction initiation beneath pre-existing buoyant lithosphere, consistent with the geochemical evidence for a subduction-related evolution. Our multi-stage forearc accretion model provides a new solution to reconcile the global *"Ophiolite Conundrum"*.

This project is part of CCFS Theme 2, Earth's Evolution, and contributes to understanding Earth's Architecture and Fluid Fluxes.

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Funded by: ARC Discovery Project, CCFS Flagship Program 1, NSFC (J.P.Z.)

Secular change in Archean crust formation recorded in Western Australia

The mechanisms that generated early Archean continental crust are controversial. Continental crust may have accumulated via horizontal accretion in modern-style subduction zones or via vertical accretion above upper mantle upwelling zones. However, the characteristics of the continental crust changes at the transition between the Archean and Proterozoic eons, suggesting that continental crust did not form in subduction zones until at least the late Archean.

In a manuscript (*Yuan, CCFS publication #649*) seismic receiver function data were used to analyse the bulk properties of continental crust in Western Australia (Fig. 1), which formed and stabilised over a billion years in the Archean. The analysis shows that the bulk seismic properties of the crust cluster spatially, with similar clusters confined within the boundaries of tectonic terranes (Fig. 2). This spatial clustering of the crustal properties is strongly indicative that these tectonic sub-units may have formed differently through time.

Local Archean crustal growth models suggest that both plume and subduction processes may have had a role in creating crust throughout the Archean. A correlation between crustal age and the bulk seismic properties of the crust reveals a trend: from about 3.5 Ga to the end of the Archean, the crust gradually thickened and simultaneously became more evolved in composition. A similar trend of Archean crustal thickening is also found in a global compilation by Keller and Schoener (*Nature, 2012*).

This trend probably reflects the transition between crust dominantly formed above mantle plumes, to crust formed in subduction zones - a transition that may reflect the secular cooling of Earth's mantle. Numerical simulations (*e.g. Johnson et al., Nature Geoscience, 2014*) show that such secular mantle cooling (decreasing mantle potential temperature (Tp), controls the overall efficiency of the Archean lower crustal delamination processes: higher Tp results in rapid and complete removal of the lower crust, while lower Tp makes the removal process less efficient. It is thus likely that the systematic crustal thickening in WA may simply reflect the secular mantle cooling process: more efficient lower crustal removal processes in the hotter Paleoarchean lead to a thin

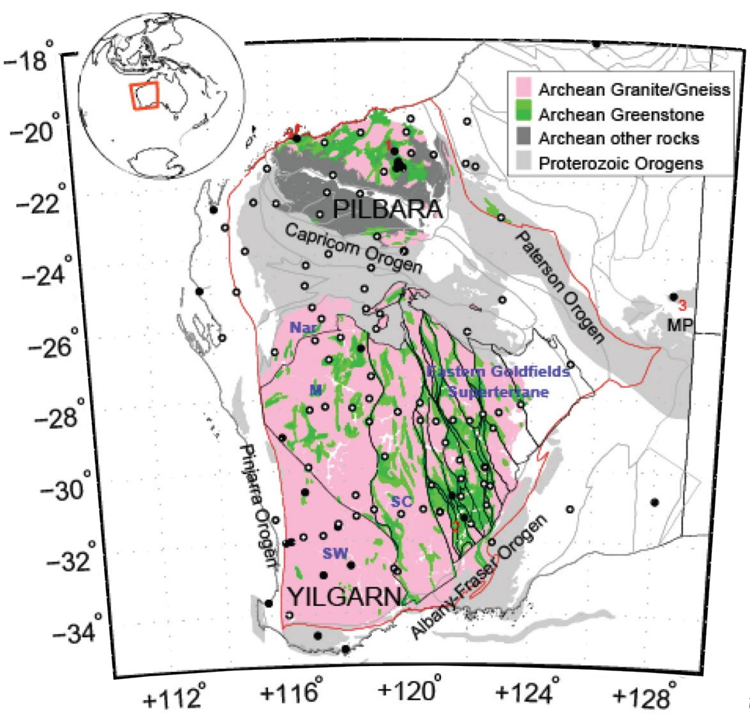

Figure 1. Simplified Archean and Proterozoic rock ages, crustal elements and seismic stations in Western Australia. Inset shows the location of the study region. Greenstone belts are shaded in green. Rock ages and large-scale crustal elements are based on 1:500k State Tectonic units map compiled by the GSWA. Terrane and domain boundaries in the Yilgarn follow Cassidy, et al. 2010. Seismic stations are shown by open (temporary deployment) and filled (permanent) circles. Labels are: Nar, Narryer terrane; M, Murchison domain; SW, Southwest terrane; SC, Southern Cross terrane; and MP, Proterozoic Musgrave Province.

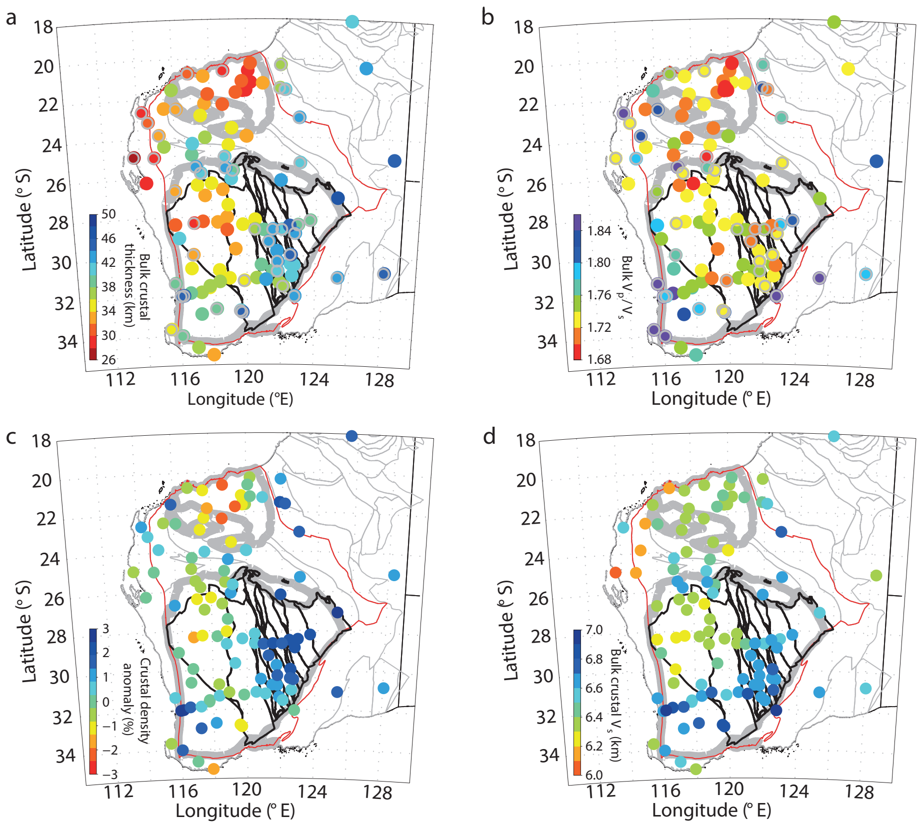

Figure 2. Spatial distribution of the crustal observations in the Western Australian craton. a-d, Bulk crustal thickness (a), Vp=Vs ratio (b), crustal density anomaly (c; Aitken et al., Tectonophysics 609, 467-479, 2013) and composite bulk crustal compressional wave (P-wave) velocity (d). The measurements are colour-coded and plotted at the seismic stations. The WA craton is contoured in red. The subdivisions of WA can be found in Figure 1.

As the mantle cooled, subduction eventually became more dominant in the late Archean (*Barley et al., Precambrian Research, 2008*); the subduction-related new magmas that were added to the continental crust may evolve to more intermediate composition (*Christensen and Mooney, Journal of Geophysical Research, 1995*).

This project is part of CCFS themes 1, 2 and 3, Early Earth, Earth's Evolution and Earth Today, and contributes to understanding Earth's Architecture.

Contact: Huaiyu Yuan

Funded by: CCFS Flagship Program 7

Pilbara crust; towards the end of Archean, the delamination processes gets sluggish and less lower crust is delaminated, resulting in a gradually thickened crust.

The overall efficiency of the lower crustal delamination processes through time can also explain the age-progressive evolution of the WA crustal composition. In the Paleoarchean, the high mantle temperature and radiogenic crust, episodes of plume activity (*Van Kranendonk, CCFS publication #492*) and delamination-driven melts (*Bedard, Geochimica et Cosmochimica Acta, 2006*) are probably the key to generating the extremely felsic crust found in the Pilbara, by multi-stage crustal fractionation. In the late Archean, if more mafic lower crust is preserved, it would result in a bulk crustal composition that is more intermediate. By this time, crustal growth in WA may be in transition to a horizontal accretion regime.

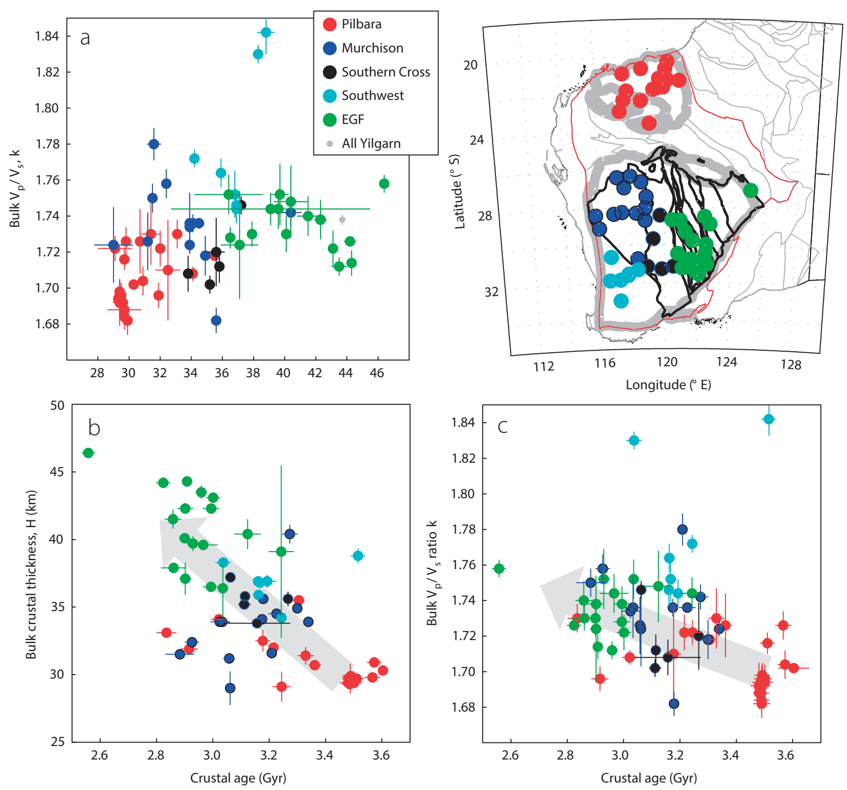

Figure 3. Clustering and temporal variations in the WA crust. a-c, Clustering in the seismic measurements (a), the age correlation of the bulk Vp=Vs ratio (b), and the bulk crustal thickness (c). Stations for each subdivision are marked on the map (inset) and labelled in a. The measurement errors of seismic observations and the errors associated with the isotopic ages are indicated. Note the large deviation of the Southwest terrane and the lack of robust measurements from the Narryer terrane, which are discussed in CCFS Publication #649.

The geometry and kinematics of hydrothermal vein emplacement in the 3.5 Ga Dresser Formation, North Pole Dome, Western Australia

Figure 1. Dense network of hydrothermal feeder veins to the Dresser Formation in the North Pole Dome.

The 3.5 Ga Dresser Formation in the Pilbara Craton of Western Australia is famous for hosting Earth's oldest convincing evidence of life, exposed in the North Pole Dome (see *Research highlight pp. 46-47*). The Dresser Formation is preserved as a ring of hills, up to 14 km in diameter, and dips shallowly away from the ca 3.46 Ga North Pole Monzogranite that was emplaced to the core of the dome as a sub-volcanic laccolith during eruption of the overlying (ca 3.45 Ga) Panorama Formation.

The Dresser Formation was previously considered to represent a quiet-water, shallow marine environment, but more recent studies suggest it was deposited in an active volcanic caldera floored by an extensive syn-depositional hydrothermal system (Fig. 1). Although the veins representing this system have been recognised as fracture fillings and syn-depositional growth faults (*e.g., Nijman et al., Precambrian Research, 1999*), no kinematic reconstruction of the offsets has previously been attempted. Such a reconstruction can constrain the regional tectonics and associated deformation: was there a regional stress field, or can the veins be related to processes directly related to magma supply and discharge within an evolving caldera system? Is there more than one vein set, and if so how do they relate to the developing caldera?

Answering these questions requires a better view of the structure of veins and their geometry and very detailed field studies of vein networks. This has involved detailed field mapping and structural analysis to define the 3-dimensional geometry of the network and the history of veining and fault-related offsets. In the field mapping phase we measured approximately 300 veins in the area (Fig. 2; B). Hydrothermal veins were measured for their strike and dip and geographic co-ordinates. As well, cross-cutting relationships between veins were documented where observed, to define the age relationships between the veins. The study area is divided into 10 separate structural blocks whose boundaries are defined by major faults (Fig. 2; A).

The measured veins in each structural block were analysed using the Dips and Stereonet computer programs. This allows determination of the principal orientation of the vein sets, the

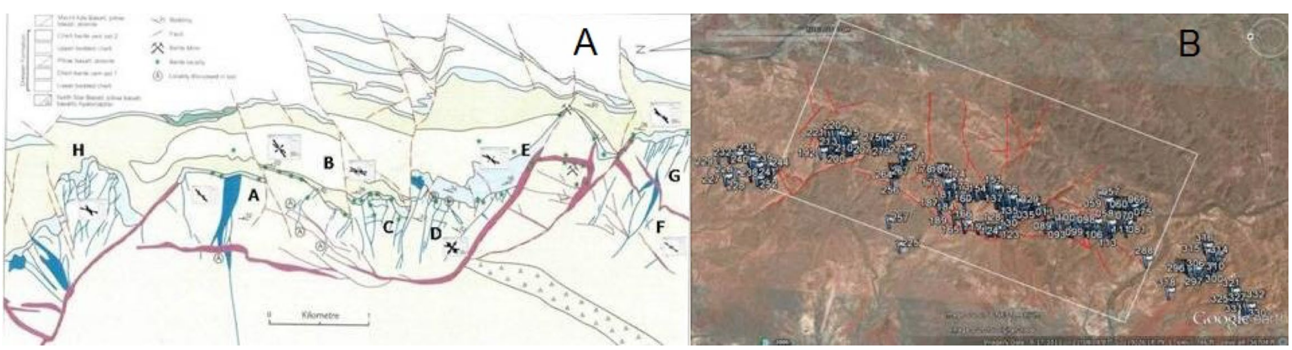

Figure 2. A) Geological map of part of the Dresser Formation, showing two sets of hydrothermal veins (dark blue and purple) and major structural blocks (A-H). Note that many veins occupy faults that offset bedded cherts (light blue) and volcanic rocks (green). B) Field stations in the study area. White rectangle outlines the area of represented in A.

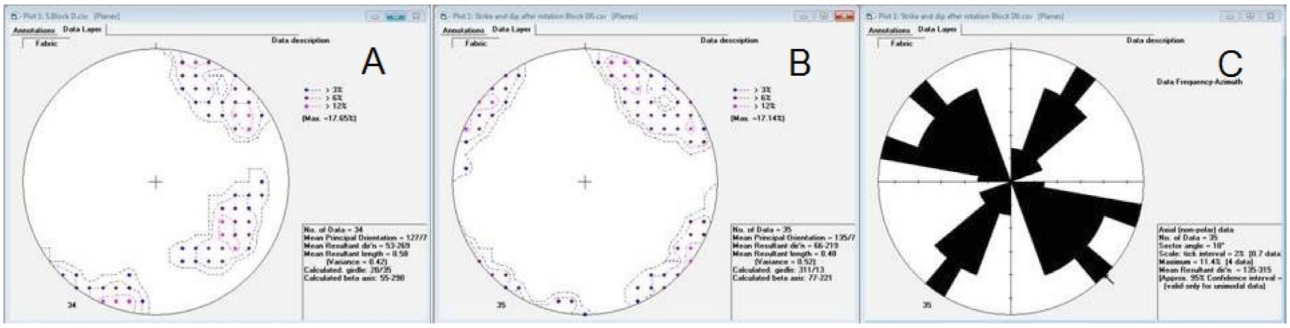

Figure 3. A) Measured orientations of veins in Block D. B) Back-rotated data of veins in block D, showing a NW-SE and NE-SW conjugate array of veins in this block prior to tilting. C) Rose Diagram of back-rotated vein data from block D.

number of vein sets in each block, and the number of vein systems in the whole of the study area. The measured data were back-rotated to horizontal by un-tilting the bedding, using the Stereonet program Georient. The back-rotated vein data thus represent the orientation of the veins in each structural block before regional tilting (Fig. 3).

This analysis indicates that almost all veins were vertical prior to tilting; therefore, Rose diagrams of each structural block were constructed, in order to identify the main direction of the veins in each block (Fig. 3; C).

The age relationships of the veins sets were studied in order to determine the relationship of the vein sets to regional deformation. The collected data also provide a better understanding of the history of events and geodynamic setting of the Dresser system. This information then will be used to develop a 4-dimensional understanding of the events that accompanied the flourishing of the earliest life on Earth.

This project is part of CCFS Theme 1, Early Earth, and contributes to understanding Earth's Architecture and Fluid Fluxes.

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Funded by: CCFS Flagship Program 4

Unraveling the Baoule-Mossi secrets: U-Pb and Lu-Hf studies of detrital zircons from southern Mali, West African Craton

The West African Craton and in particular its southern portion represented by the Leo Man rise host a number of world class and base metal systems. The Leo Man is divided into the Archean Kénéma-Man in the western portion and the Baoulé-Mossi in the eastern region (Fig. 1). The Kénéma-Man domain is characterised by Archean age rocks and covers large portions of Sierra Leone, Liberia, Côte d'Ivoire, and Guinea. Its counterpart, the Baoulé-Mossi is characterised by Paleoproterozoic age rocks that are commonly referred to as the Birimian terranes. The Baoulé-Mossi covers most of the geology of Burkina Faso, Ghana, Mali, Niger, Côte d'Ivoire, and Guinea. The Birimian terranes *sensu lato* are comprised of relatively narrow volcano-sedimentary basins and linear or/and arcuate volcanic belts known as greenstone belts-basins; associated granitic-felsic intrusive terranes; the contemporaneous or slightly younger sedimentary basins, such as Kuasi, Siguiri, and Sunyani, and the late-basins such as the Tarkwa, and Bui.

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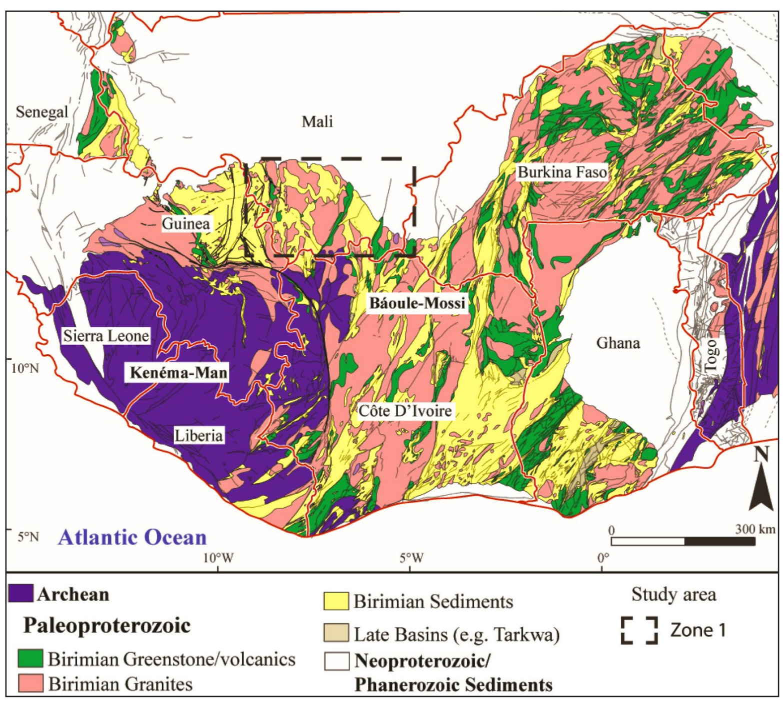

Figure 1. Simplified geological map of the Leo-Man rise (modified after the BRGM SIGAfrique map, (Milési et al., 2004) and the West African Craton (after Gueye et al., 2007).

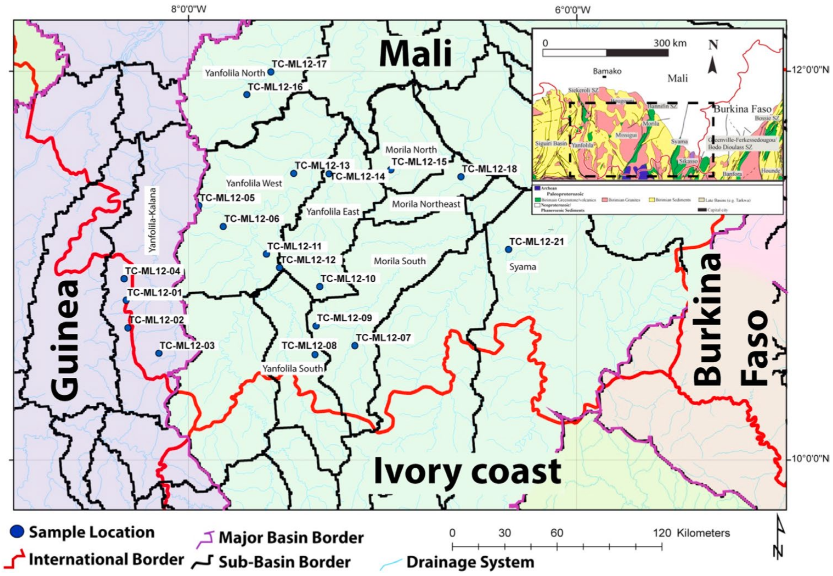

Figure 2. Sample distribution across southern Mali. Purple region represents the Niger River Basin while the light green region corresponds to the Bani River Basin. Basin and sub-basins after Lehner et al., 2006.

Despite the occurrence of a large number of mineral deposits, the region is still poorly understood and subject to much controversy. One of these controversies is the distinction between the Archean and Paleoproterozoic boundaries. It is also believed that the Paleoproterozoic Baoulé-Mossi is the result of mostly juvenile activity with limited interaction with older Archean material. In order to shed light onto the matter, this study analysed zircons collected from small streams, creeks and dry gullies in the area's modern drainage system. Zircons were collected from twenty sites across southern Mali covering the Niger and Bani river basins. The Niger River was sampled across 4 sites representing one sub-basin and the Bani River was sampled across eighteen sites representing 8 sub-basins (Fig. 2). A total of 599 zircons from the Niger River and 2254 zircons from the Bani River basin were selected as part of the study. U-Pb analyses were conducted on 295 zircons of the Niger River and 792 zircons of the Bani River, after which 92 zircons of the Niger River and 284 zircons from the Bani River were analysed for Lu-Hf isotopes.

The U-Pb results gave Paleoproterozoic ages between 2400 and 2070 Ma. This age range is in agreement with the historical record across southern Mali. These Paleoproterozoic age zircons are considered to be of magmatic origin and show limited metamorphic overprints. They yielded Hf-isotope compositions that indicate model ages between 2800 and 2100 Ma. The spread in Hf-isotope composition points towards a mixing between a juvenile source and a crustal source as old as 2800 Ma.

A second group of zircons yielded U-Pb ages between 3600 and 2100 Ma and Hf model ages between 3600 and 2800 Ma (Fig. 3). This second group presents characteristics that are congruent with long transport due to mostly sub-rounded to rounded crystal morphology. It is also likely that streams and small rivers transported zircons from the Archean Kénéma-Man domain to the Baoulé-Mossi domain because the basin drainage is mainly in a south-southwest to north-northeast direction. Multiple grains were analysed in both rims and suspected inherited cores and showed no variation in ages. Thus, no Proterozoic zircons with Archean age cores have been identified.

The identification of Archean zircons in the region suggests greater interaction between the Baoulé-Mossi and Archean Kénéma-Man domains. Although zircons of the Baoulé-Mossi domain generally confirm its juvenile origin, some of those Paleoproterozoic grains have Hf-isotope composition that indicate reworking of an older crust at a larger scale than previously recognised.

This project is part of CCFS Theme 2, Earth's Evolution, and contributes to understanding Earth's Architecture.

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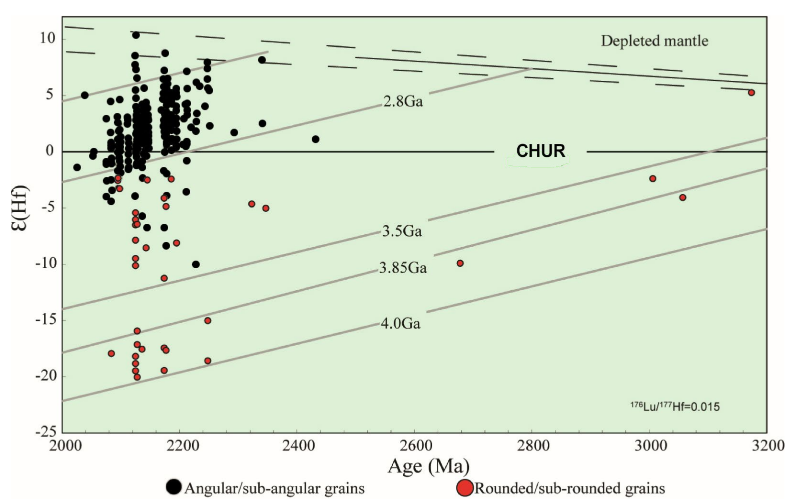

Figure 3. εHf vs. U-Pb age in Ma showing the distribution of the angular to sub-angular grains (black circles) and the sub-rounded to rounded grains (red circles).

Disequilibrium-induced initial Os isotopic heterogeneity: implications for dating and source tracing

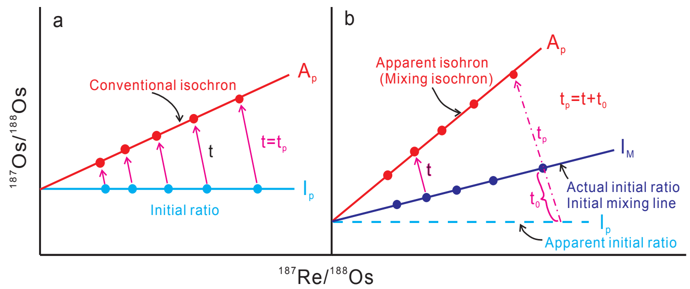

Figure 3. Illustration of the cases of binary mixing on the Re-Os isochron diagram, (a) K = 0; the initial Os isotopic ratios of the two mixing components were in equilibrium after diffusion during mixing (or the mixture was derived from a single homogeneous component). The isochron is a conventional isochron (Ap) with initial $^{187}Os/^{188}Os$ (Ip), and the observed apparent isochron age (tp) is equal to its formation age (t); (b) K ≠ 0; the initial Os isotopic ratios of the two mixing components were not in complete equilibrium after diffusion during mixing. The mixing line (Ap) represents the combination of an initial mixing line (IM) and the ingrowth of ^{187}Os since formation (t). Such an apparent isochron (AP) yields a geologically meaningless age (tp).

The Re-Os isotopic system has been widely used to date a variety of materials ranging from mafic-ultramafic rocks and sulfides, to black shale, and even oil. Given their chalcophile and siderophile geochemical behaviour, both Re and Os have a strong affinity to trace phases (e.g. sulfides and alloys), and thus their budgets in these rocks are controlled mainly by these trace phases. The unequal distribution of these discrete trace phases (the nugget effect) leads to poor reproducibility of both Re and Os concentrations that limits applications of the isotopic system. However, its effect on the scale of initial Os isotopic heterogeneity is unclear. To clarify these uncertainties, it is necessary to investigate whether homogenisation of the Os isotopic composition was achieved in these rock systems during their formation.

Replicate analyses of gram aliquots of single basaltic powders (one of reference material BHVO-2 and three of the Hatu basalts from the western Junggar region, China) show large variations in both Os concentrations and isotopic ratios.

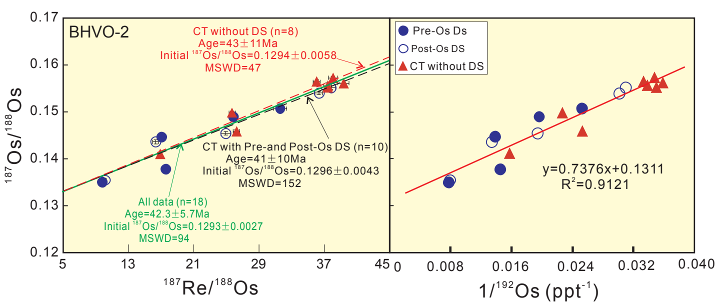

Figure 1. Measured $^{187}Re/^{188}Os$ vs $^{187}Os/^{188}Os$ (a) and inverse of ^{192}Os concentration vs $^{187}Os/^{188}Os$ (b) for BHVO-2 (true age <100 years). All regressions here were calculated using the program Isoplot 3.00 [Ludwig, 2003]- uncertainties - 2SE. The linear regression equation and R2 value are shown on the diagram here. These good positive covariations suggest binary component mixing.

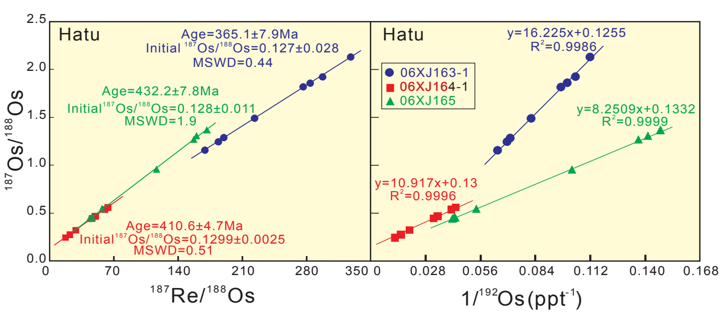

Figure 2. (a) Re-Os isochron diagram for replicate analyses (n = 8) of each of the three Hatu basalts (true age ca 315 Ma). The three samples exhibit three different apparent isochron ages with different initial $^{187}Os/^{188}Os$ ratios. (b) $^{187}Os/^{188}Os$ plotted against $1/^{192}Os$ for replicate analyses of the Hatu basalts. Error bars are shown when bigger than the symbols. All three samples show positive slopes with 06XJ163-1 having a steeper slope.

Duplicate analyses of a single powered whole-rock sample including both Hatu basalts and international reference rock (BHVO-2) defined good apparent Re-Os isochrons and linear trends between $1/^{192}Os$ vs $^{187}Os/^{188}Os$ (Fig. 1 and Fig. 2). These relationships signify disequilibrium-induced small-scale Re-Os heterogeneity and no individual analysis can represent the initial Os isotope composition of the whole-rock sample (their source composition). Because in most cases only one analysis was conducted on 1-2 g of a randomly selected aliquot of powdered whole-rock samples, this study raises the issue of whether an individual analysis can be representative of the source of the whole rock. This is especially true for rock units with large ranges of measured $^{187}Re/^{188}Os$ and $^{187}Os/^{188}Os$ ratios.

Apparent Re-Os isochrons can be generated through binary mixing without complete isotopic equilibrium at the time of formation, primarily due to limited diffusional exchange of Os isotopes between refractory Os-bearing inclusions, sulfides, their host minerals and the magma under mantle conditions (Fig. 3). The regressed initial Os isotopic composition may not represent the true value of the mantle source. Thus, when using the Re-Os isotopic system to date and to trace the source of basaltic rocks or other rocks with relatively low Os concentrations, it is necessary to consider whether the initial Os isotopic composition was heterogeneous or whether it had reached complete isotopic equilibrium. The results obtained in this study also pertain to Re-Os dating of low-temperature systems such as black shales, crude oil and bitumen.

This project is part of CCFS Theme 2, Earth's Evolution, and contributes to understanding Earth's Architecture.

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Funded by: Wang ARC Future Fellowship, National Natural Science Foundation of China (41173038)

Heaven on Earth: '*nebular*' mineral assemblages from Mt Carmel, Israel

The minimum oxygen fugacity (fO_2) of Earth's upper mantle probably is controlled by metal saturation, as defined by the Iron-Wüstite buffer reaction FeO→Fe + O. However, moissanite (SiC) is found in kimberlites worldwide, and an extensive suite of super-reduced minerals, including SiC, alloys and native elements, occurs in peridotite massifs in Tibet and the Polar Urals. These occurrences suggest that more reducing conditions (fO_2 = 5-6 log units below IW) must occur locally in the mantle. Unfortunately, these occurrences are known almost entirely from mineral separates, and thus lack spatial mineralogical context.

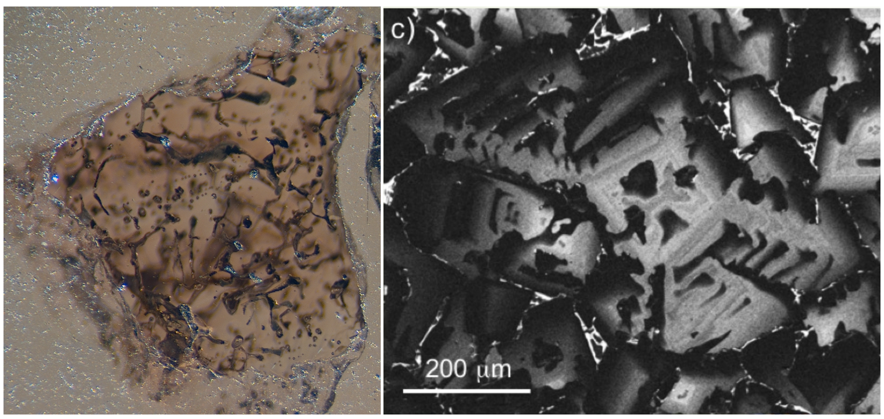

Figure 1. Left: transmitted-light image of 1-mm corundum grain from Mt Carmel, showing network of melt inclusions within and between corundum crystals. Right: cathodoluminescence image of corundum crystal showing skeletal/hopper growth; dark zones reflect high concentrations of Ti^{3+} in corundum, and darkest colours are adjacent to melt pockets.

In an ongoing collaborative research project with Shefa Yamim (A.D.M.) Ltd (Akko, Israel), we have found that aggregates of corundum crystals ejected from Cretaceous volcanos on Mt Carmel, North Israel, contain trapped melt pockets (Fig. 1) with high-temperature mineral assemblages that require extremely low fO_2 (IW -10). Over 65 different phases have been recognised; half of these have not been described previously as minerals.

The corundum crystals show spectacular variation in cathodoluminescence (CL), varying from light pink to dark pink to black, corresponding to a progressive increase in Ti content. Stoichiometry indicates that Ti is present as Ti^{3+}, i.e. a strongly reduced form. The CL images (Fig. 1) and EBSD studies show that most crystals are skeletal and grew as aggregates of hopper crystals, implying rapid crystallisation from melts supersaturated in Al_2O_3.

The pockets contain four basic types of melts. Type S (silicate), the most abundant, consists of crystalline phases, commonly including tistarite (Ti_2O_3), set in a matrix dominated by Ca-Al-Si-Ti-Zr-K oxides (Fig. 2). This matrix usually is either glass or very finely crystalline; it is amorphous in terms of Raman spectroscopy. Some inclusions show quench structures with radiating blades of anorthite and/or needles of unidentified REE-rich phases in the Ca-Al-Si glass, while in others the matrix has crystallised to an assemblage including anorthite and several undescribed Ca-K-Mg-Al silicates and oxides. None of the silicate or oxide phases in the Type-S melt pockets contain detectable levels of Fe or Ni.

Type A (alloy; Fig. 3) pockets were Fe-Ti-Si-C-P melts, and have crystallised to a range of phases, including gupeiite (Fe_3Si), FeTiSi, FeTi and TiC (khamrabaevite). Type N (nitride; Fig. 4) is represented mainly by osbornite (TiN with 12.5-16% N), intergrown with TiB_2; the identity of both phases has been confirmed by Dr Martin Saunders (UWA), using TEM electron diffraction. TiO has also been found together with TiN. Type N assemblages commonly occur in complex rectilinear 3-D networks, which may cross Type

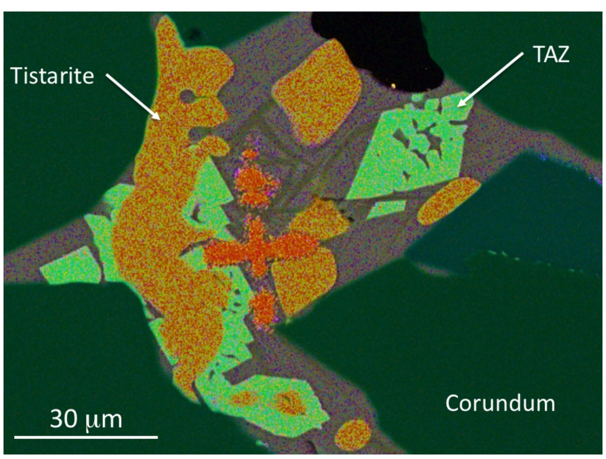

Figure 2. Tistarite and TAZ phase in melt pocket; dark matrix is Ca-Al-Si glass with darker quench needles of anorthite; red phase is TiN. Note euhedral corundum crystals forming boundaries to melt pocket.

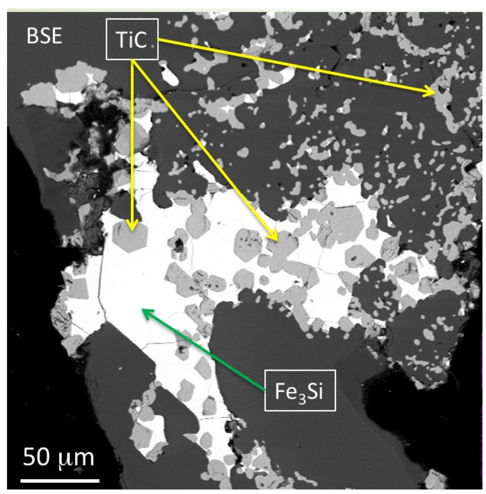

Figure 3. Type A melt pocket between euhedral corundum crystals; TiC crystallising from an Fe-Ti-Si-C melt have been trapped by the growth of the corundum crystals, confining the melt to the interstitial spaces.

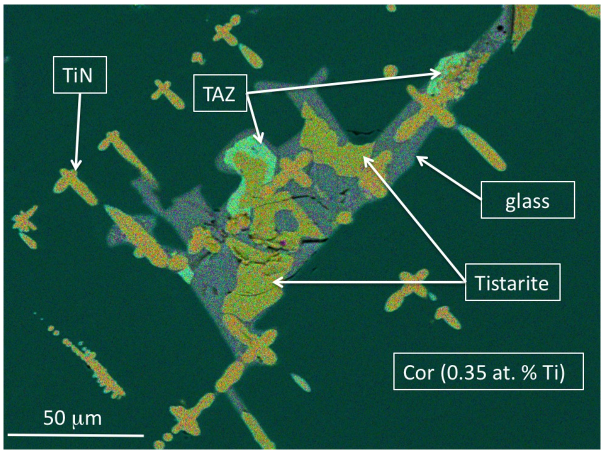

Figure 4. Type S and Type N melts; the TiN appears to fill rectilinear channels in the corundum, related to skeletal growth (Fig. 1).

S pockets (Fig. 4). Type D (desilicated; Fig. 5) pockets consist of phases with no Si, including native vanadium, grossite ($CaAl_4O_7$), hibonite ($CaAl_{12}O_{19}$) and fluorite.

The textural relationships in and among the melt pockets suggest that the different melts were mutually immiscible. They can be found in different areas of the same inclusion (especially where these are partially necked-down), and in separate inclusions in the same corundum grain; the apparent separation may simply reflect 2-D sectioning of complex 3-D structures (Fig. 1).

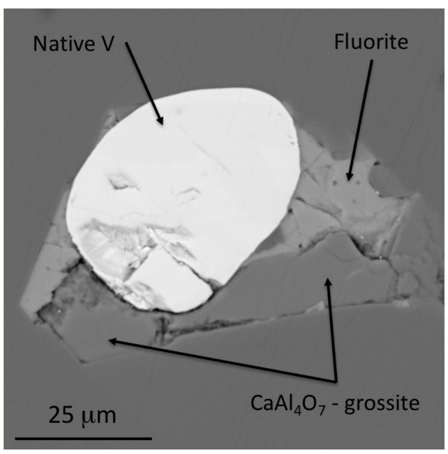

Figure 5. Type D (Si-free) melt pocket with native V, grossite and fluorite.

The presence of glass with quench structures implies that the evolution of the melts was halted by eruption of the host magma. The peritectic crystallisation of corundum+melt → anorthite indicates crystallisation at depths of 30-100 km (i.e. within the lithospheric mantle) and temperatures in excess of 1450 °C. Available experimental data on other phases (usually at 1 atm. pressure) also indicate magmatic temperatures.

One of the most abundant phases in the Type S pockets is tistarite (Ti_2O_3), previously known only as a single grain (associated with TiC and corundum) from the Allende carbonaceous chondrite. These reduced phases are believed to have formed as high-T condensates during the early evolution of the solar nebula, when the fO_2 was 10^{-19}, ca 10 log units below the IW buffer (Fig. 6), because the solar wind consisted almost entirely of hydrogen.

Other *'nebular'* phases in the Mt Carmel assemblage include SiC, grossite, hibonite, osbornite, gupeiite and wassonite (TiS), all typically found in carbonaceous chondrites. Similar high-T, very low-fO_2 conditions must have existed locally in the Cretaceous upper mantle beneath Mt Carmel. We propose that the development of super-reducing conditions in Earth's upper mantle may reflect the mixing of deep-mantle CH_4+H_2 fluids with mafic magmas in volcanic plumbing systems. Such mixing can lead to desilication of the magma, oversaturation in Al_2O_3 and *'dumping'* of corundum in magma conduits. These remarkable samples represent a mantle environment, and a part of the global carbon cycle, that were previously unrecognised, and a process of fluid transfer that may be much more widespread.

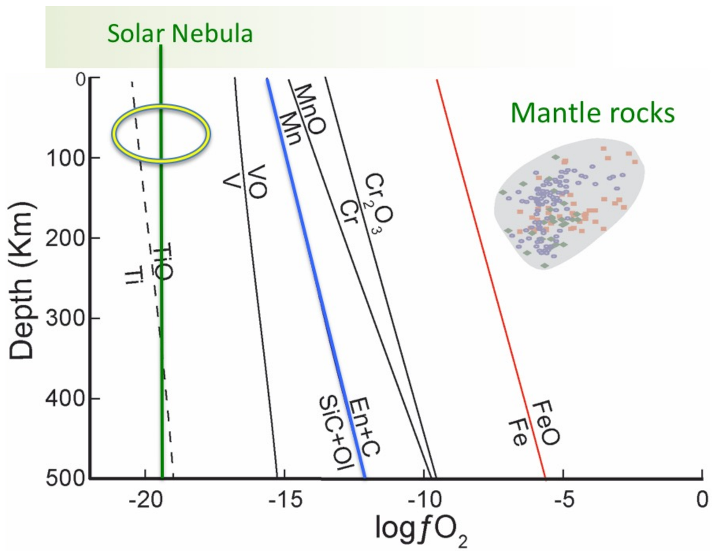

Figure 6. Some fO_2 buffer curves relevant to the assemblages in the melt pockets. The final conditions of crystallisation probably lie within the green oval, where fO_2 is similar to that in the early solar nebula. The grey field illustrates estimates of fO_2 in peridotite xenoliths derived from the lithospheric mantle.

This project is part of CCFS Themes 2 and 3, Earth's Evolution and Earth Today, and contributes to understanding Earth's Fluid Fluxes.

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Funded by: CCFS Flagship Program 1

Isotopic mapping of Archaean lithosphere to target orogenic gold and magmatic Cu-Ni-P

Steep penetrating lithospheric structures are pathways for focused mass and energy flow from mantle to crust. Mineralisation emplaced from the mantle into the crust is likely to be distributed along these pathways, a concept supported by empirical associations between mineral systems and lithospheric architecture. A large portion of today's continents (<70%) is thought to be underlain by Archaean continental lithospheric mantle, which may have been instrumental in localising much of the mineralisation of its time and in many succeeding events. As high-quality greenfield mineral discoveries decline, mapping the Archaean crust-mantle evolution through time and space has potential to highlight prospective lithosphere and aid in targeting mineral systems.

Despite a rich geological record of Archaean crust, conditions and geodynamic processes characterising the Archaean remain contentious. Interpretations inferred from petrological, geochemical and geophysical signatures are fraught with the prospect that these signatures reflect overprinting by deformation and metamorphism. An increasingly popular approach to interrogate the crustal record capitalises on the ability of the zircon lattice to concentrate useful radiogenic (Pb, Hf) and stable (O) isotopes and trace elements, and the mineral's resistance to subsequent resetting of these systems by tectonothermal reworking.

Results from *in situ* U Pb geochronology on igneous zircons of the Marmion Terrane (3.02 - 2.68 Ga), Wabigoon Superterrane, Western Superior Craton, Canada help constrain the cryptic growth of the crust across time and space. In conjunction with field-based studies, this has highlighted a shift in geodynamics at ~2.8 Ga, and allows us to explore relationships to mineral system distribution. As a uniquely preserved natural laboratory within the world's largest Archaean craton, insights gained

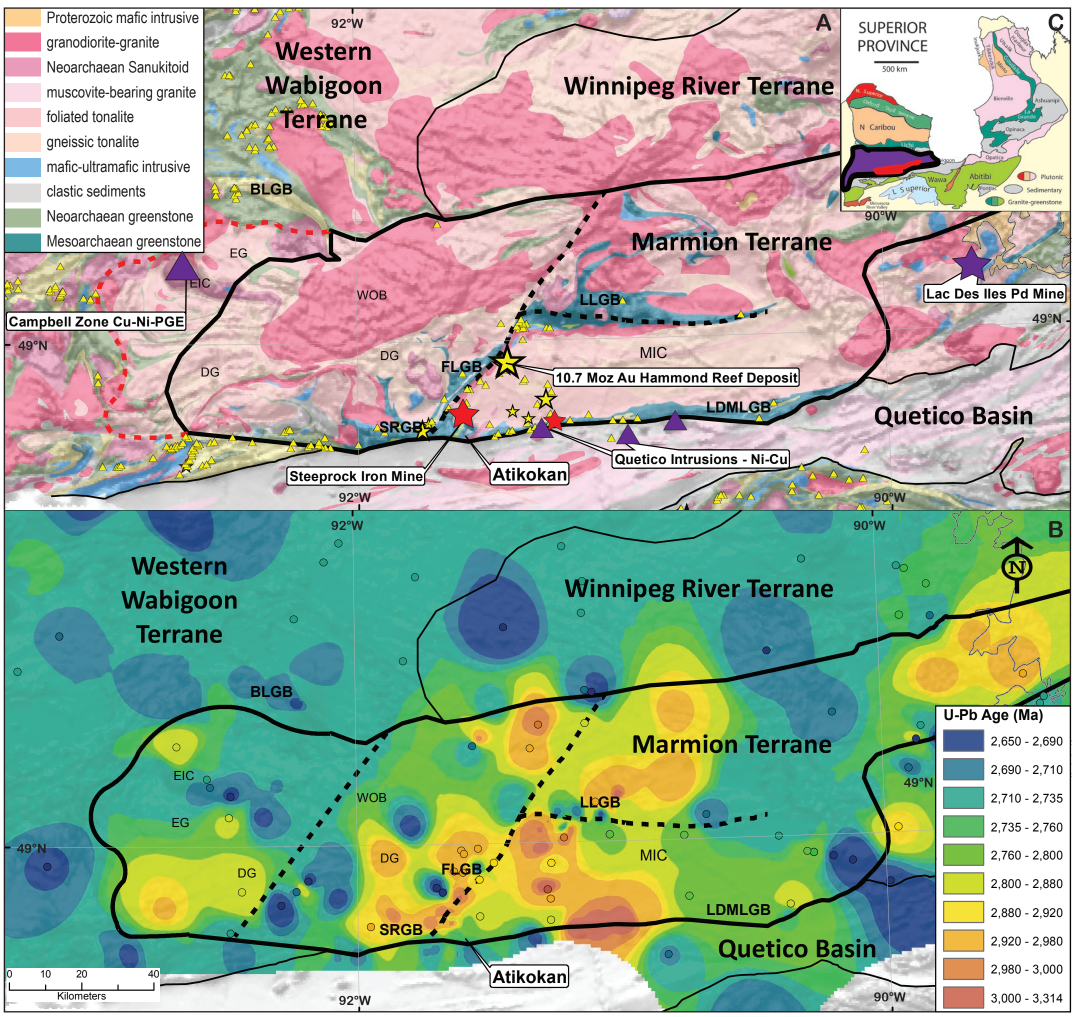

Figure 1. A. Geological map showing terrane boundaries of Stott (2011). Hatched boundaries are significant lithospheric structures. Red boundary is revised by this study. Triangles correspond to mineral occurrences, stars to past-producing mines (gold – yellow, iron – red, Ni-Cu-PGE – violet). B. Contour map based on U-Pb ages compiled from previous workers (mainly by TIMS) and this study by SHRIMP, shown in colour-coded circles corresponding to the colour scheme of the contours. Only ages interpreted as magmatic are included. C. Inset showing the location of the Marmion Terrane (red) within the Wabigoon Superterrane (violet) of the Superior Craton.

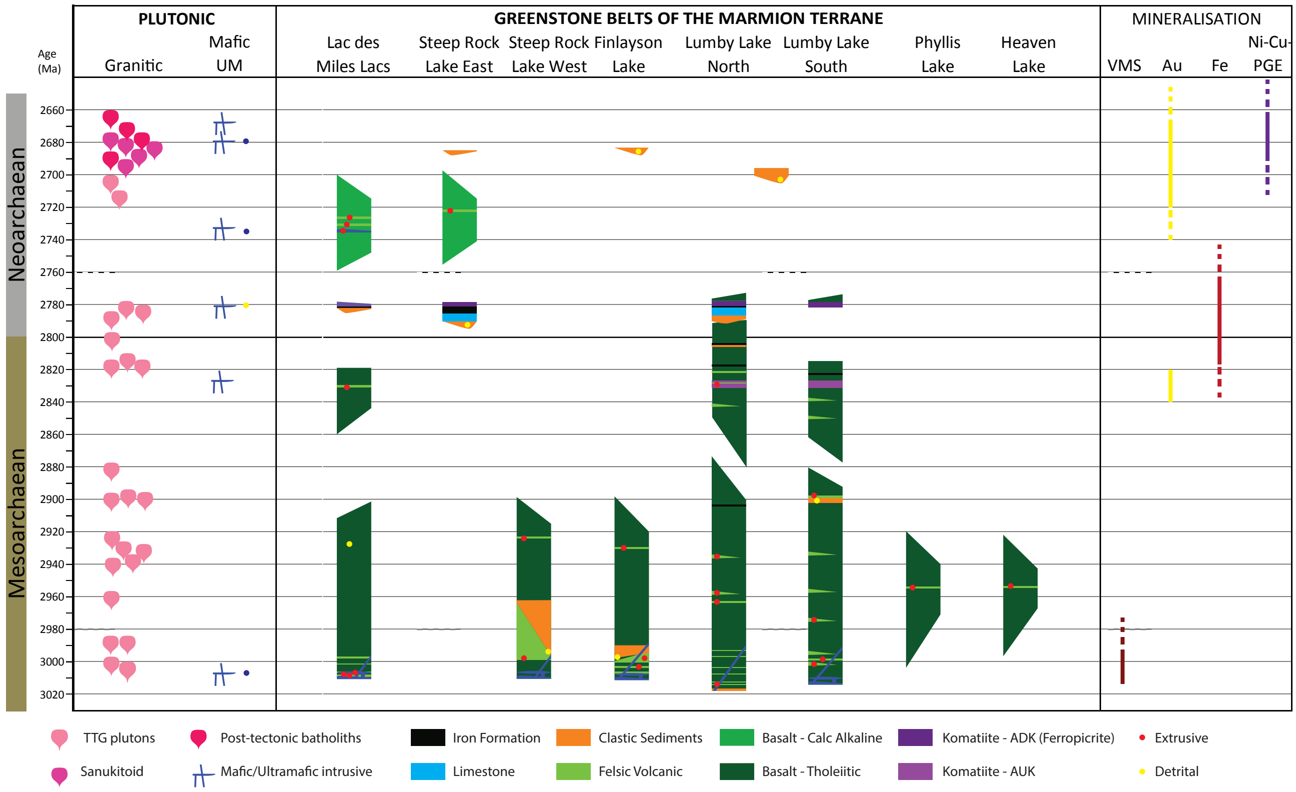

Figure 2. Stratigraphic compilation of the Greenstone belts within the Marmion Terrane. Ages are given by red (extrusive) and yellow (detrital) circles. Corresponding plutonic events are illustrated at the left. Age constraints on granitic intrusions are provided by U-Pb geochronology in zircons; blue circles indicate mafic events constrained by U-Pb geochronology in baddeleyite. Timing of mineralisation is constrained stratigraphically (VMS, Fe), by Pd-Pd ages in galena (Au) and by crystallisation ages (Ni-Cu-PGE).

here have potential to shed light on global crustal growth and geodynamics.

In the Western Superior, linear east-trending granite greenstone terranes are separated by highly metamorphosed and fault-bounded metasedimentary basins (Fig. 1c). The Marmion Terrane, with a western boundary revised by this study, stands out as the most coherent Mesoarchean block in the Wabigoon Superterrane. Isotopic patterns highlight a northeast-trending structure that is cryptic in the geology (western hatched line, Fig. 1b). Another northeast-trending structure, the Marmion Shear Zone (MSZ) appears to have controlled the significant gold deposits of the terrane (eastern hatched line, Fig. 1b). The focus of later tectonothermal events along these structures supports an interpretation of deep lithospheric structures in a northeast orientation.

Supracrustal rocks record a significant change across the Meso- to Neoarchaean boundary (Fig. 2). Cyclic tholeiitic volcanism with minor aluminum-undepleted komatiites dominates the 3.02 - 2.82 Ga record and provides evidence for high-degree partial melting of the mantle at depths above 8 GPa. The geochemistry of these rocks is analogous to those of oceanic plateaus, such as the Ontong Java Plateau. After 2.8 Ga the Marmion terrane was uplifted. Conglomerate channels were eroded into the granitic basement, and stromatolitic limestone and iron formations were deposited. Pyroclastic aluminum-depleted komatiite was then deposited, indicating much deeper mantle melting (Fig. 2). The uplift may reflect development of a depleted lithosphere which may be related to subsequent melting at greater depths.

Subsidence was followed by a shift to more calc-alkaline mafic to intermediate volcanism from 2.74 - 2.72 Ga on the southern margin of the terrane, reflecting melting of a fluid-fluxed mantle. Basin inversion accompanied ongoing transpression during the Kenoran orogeny and late Timiskiming-type sedimentation was localised in the synclinal axes of Mesoarchean greenstone belts and along the active southern margin of the terrane at 2.7 Ga. The main gold mineralisation was emplaced in the oldest tonalitic rocks at 2.7 Ga, along the steepest age gradients proximal to the reactivated MSZ and Quetico Fault, which marks the boundary between the Marmion Terrane and the Quetico basin to the south (Fig. 1). Gold mineralisation exploited a long-lived architecture during a time of favourable geodynamics.

This project is part of CCFS Theme 2, Earth's Evolution, and contributes to understanding Earth's Architecture.

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Funded by: CCFS Flagship Program 2

The Ivrea Zone Pipes: new light on ore-forming processes in the deep continental crust

Our ability to discover new mineral resources is challenged today partly due to the limited predictive capability of the traditional approach based on analogue deposit models. Recently, a new conceptual framework, the mineral system approach, has been proposed, which enables more powerful predictive capability for mineral exploration. This project tests the hypothesis that the genesis of sizeable mineral deposits is the end product of self-organised critical systems operating from the scale of the planet all the way to the very focused environment where ore deposits can form. The mineral system approach represents a step change in the way we investigate ore-forming processes, whereby we look at the evolving relationship between the localised setting of anomalous metal resources and processes operating at the scale of the planet. Prior to the advent of this concept, single deposits were documented in detail as unique occurrences. However, this approach failed to focus on the commonalities among various occurrences and, more importantly, the larger-scale architectural framework that hosts them. The new rationale now takes on a more holistic approach acknowledging that the genesis of mineral occurrences required the conjunction in time and space of three main independent parameters: fertility, lithosphere-scale architecture, and favourable transient geodynamics.

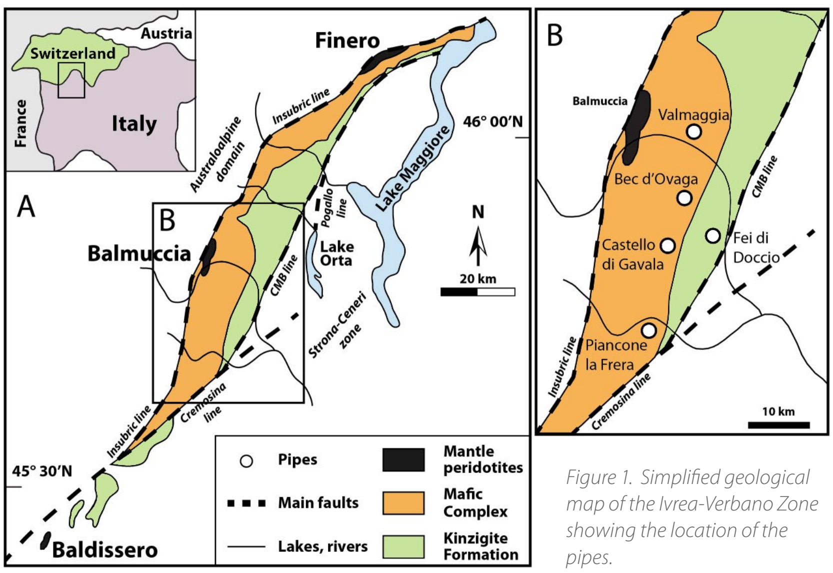


Figure 1. Simplified geological map of the Ivrea-Verbano Zone showing the location of the pipes.

This conceptual framework forms the basis of the present project, which focuses on a series of alkaline mafic-ultramafic pipes, rich in sulfides and hydrous minerals, that intruded the lower continental crust of the Ivrea-Verbano Zone in the Italian Western Alps (Fig. 1). The pipes are relatively small and primarily composed of a matrix of subhedral to anhedral amphibole (pargasite), phlogopite and orthopyroxene that enclose sub-centimetre-sized grains of olivine. The 1 to 5 m-wide rim portions of the pipes locally contain significant blebby and disseminated Fe-Ni-Cu-PGE sulfide mineralisation. Stratigraphic relationships, mineral chemistry, geochemical modelling and phase equilibria suggest that the pipes represent open-ended conduits within a large magmatic plumbing system. The earliest formed pipe rocks were olivine-rich cumulates, which reacted with hydrous melts to produce orthopyroxene, amphibole and phlogopite. Sulfides precipitated as immiscible liquid droplets that were retained within a matrix of silicate crystals and scavenged metals from the percolating hydrous melt, derived by partial melting of a metasomatised continental lithospheric mantle.

New high-precision chemical abrasion TIMS U-Pb dating of zircons from one of the pipes indicates that these pipes were emplaced at ca 250 Ma, following partial melting of lithospheric mantle pods that were metasomatised during the Eo-Variscan oceanic to continental subduction (420-310 Ma). The thermal energy required to generate partial melting of the metasomatised mantle was most likely derived from crustal extension, lithospheric decompression and subsequent asthenospheric upwelling during the orogenic collapse of the Variscan belt (<300 Ma), as shown in Figure 2. If the pipes had been emplaced in an active compressional environment during the Variscan continental collision, as opposed to the extensional post-orogenic setting constrained through the high-precision geochronology presented in this study, their magmatic plumbing would have attained self-organising criticality with the establishment of high-flux conduits. This would have led to focused energy and mass flux transfer from the mantle into the crust, with the potential for the formation of sizeable orthomagmatic deposits, rather than the modest occurrences that actually formed.

In fact, rather than through a network of self-organised high-flux conduits, mantle-derived magmas trickled through a series of lower-energy pipes, producing a slow and persistent flux of magmas through the interface between the lithospheric mantle and the continental crust. In other words, the magmatic plumbing system that originated the pipes did not self-organise, with the result that high-flux networks were not established and no major ore-forming process occurred. However, even if this process of metal and volatile transfer from the lithospheric mantle to the base of the continental crust is not necessarily conducive to the synchronous genesis of economic mineral deposits, it can be a very effective mechanism to fertilise the

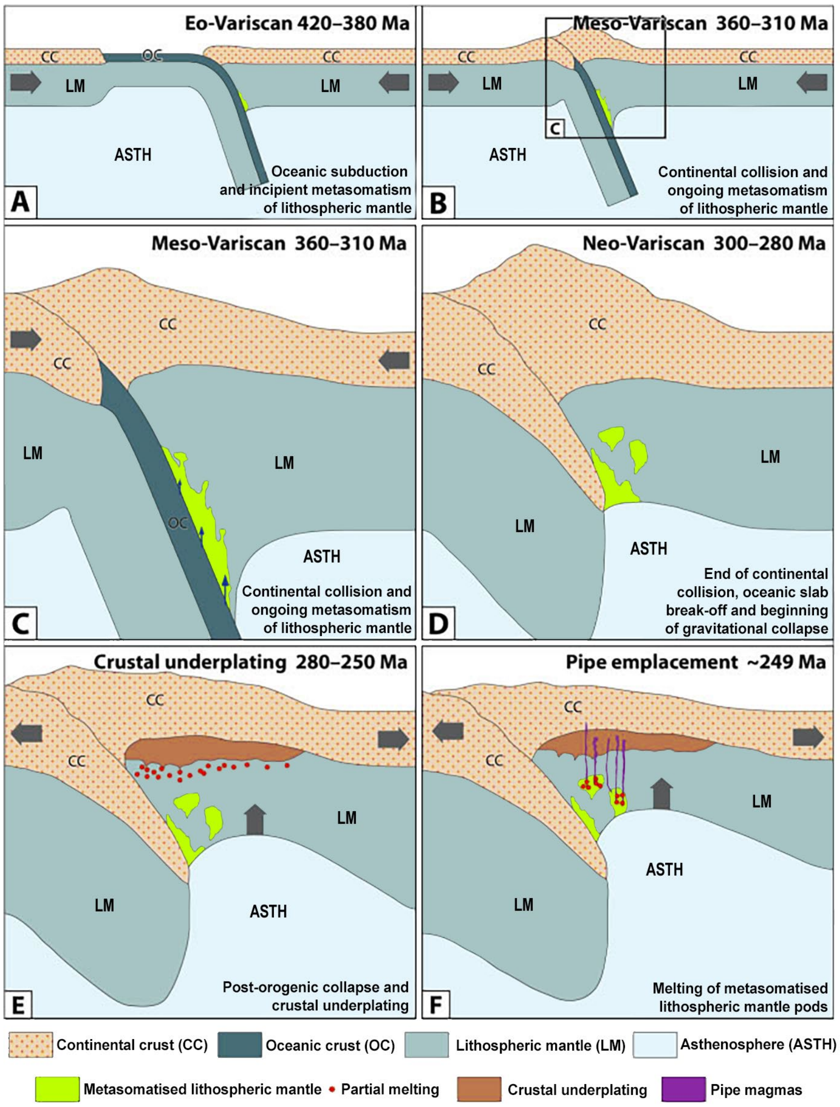


Figure 2. Schematic illustrations of the geodynamic evolution that facilitated the genesis of the pipes. (A) Early oceanic subduction in the Eo-Variscan (420-380 Ma) initiating metasomatism of the lithospheric mantle. (B, C) Continental collision and ongoing metasomatism of the lithospheric mantle in the Meso-Variscan (360-310 Ma) create pods of metasomatised mantle (cf. D). (D) End of the continental collision and beginning of the gravitational collapse in the Neo-Variscan (300-280 Ma). (E) Post orogenic collapse, crustal extension and asthenospheric rise cause decompression melting of the lithospheric mantle and initiate the underplating of the continental crust. (F) Further extension and asthenospheric rise cause partial melting of the metasomatised mantle pods, facilitating the intrusion of the pipe magmas into rocks of the upper lithospheric mantle and lower continental crust.

notably dry and restitic lower continental crust. Accordingly, even without necessarily generating significant syngenetic Ni-Cu-PGE mineralisation, this process has the potential to add metals and volatiles into the base of the continental crust, thus seeding the ground for the genesis of later mineral systems. This process could represent an effective mechanism to enhance the metal endowment of continental block margins and paleo-margins.

This project is part of CCFS Themes 2 and 3, Earth's Evolution and Earth Today and contributes to understanding Earth's Architecture and Fluid Fluxes.

Contacts: Marco Fiorentini, Marek Locmelis, Tracy Rushmer, John Adam, Steve Denyszyn, Ricardo Arevalo

Funded by: CCFS Flagship Program 2, Fiorentini ARC Future Fellowship

CCFS honours & postgraduates

HONOURS

COMPLETED 2015

Jack Adams: Chromian spinel - Hydrous melt: Integrating isotope labelling and NanoSIMS (UWA)

Sarah Chamberlain: Geochronology, palaeomagnetism and magnetic fabric of mafic dykes near the Darling Scarp and palaeogeography of Western Australia (CU)

Haydn White: Sub-micron imaging of cation and $D_2{}^{18}O$ exchange during K-feldspar replacement under hydrothermal conditions (UWA)

CONTINUING 2016

Wendy Dang: Implications for life on Mars at Gusev Crater and Nili Patera using a terrestrial analogue at the North Pole Dome, Western Australia (UNSW)

COMMENCING 2016

Chris Guldbrandsen: The role of microbial precipitation of '*buckshot pyrite*' in the 2.76 Ga Hardey Formation, Fortescue Group, Pilbara, Australia (UNSW)

Brendan Nomchong: The origin of clotty-textured (thrombolitic) microbialites at the rise of atmospheric oxygen: The c. 2.4 Ga Turee Creek Group, Western Australia (UNSW)

Georgia Soares: The developmental significance of stromatolite complexity across the rise of atmospheric oxygen: The c. 2.4 Ga Turee Creek Group, Western Australia (UNSW)

Luke Stellar: Boron and the origin of life: geochemical analysis of ancient tourmaline crusts, Recent boron-rich muds, and synthesised boron-rich products (UNSW)

MASTERS OF RESEARCH, MQ

From 2013, the honours program at Macquarie University was replaced by a two-year Masters of Research (MRes) combining advanced coursework with research training to better prepare research students for further postgraduate study. The MRes aligns Macquarie's HDR program with those of many international universities and allows for a smoother transition into international postgraduate programs.

From 2014, the MRes or equivalent is the prerequisite for enrolling in Macquarie's postgraduate research (PhD) program. This change fulfils one of the CCFS goals - introducing high-level postgraduate coursework units.

COMPLETED 2015

Anthony Lanati: Determining the role of water in mantle conductivity

Alexandre Lemenager: Numerical modelling of the Sydney Basin using temperature dependent thermal conductivity measurements

Uvana Meek: Reactive fluid flow in the lower crust

Josephine Moore: Grain boundary characterisation of Alpine Fault rocks

CONTINUING 2016

Cameron Brown: Geomechanical stability of granular asteroids

Victoria Elliott: Modification of zircon during melt-rock interaction, Fiordland, New Zealand

Jean-Antoine Gazi: Accretion of planetismals: A view from Carbonaceous Chondrites (*pictured below*)

Mitchell Gerdes: Cryptic Amphibole and H_2O fractionation from melts in volcanic arc settings: Evidence in xenoliths from Batan Island, Philippines

Colleen McMahon: Effects of lithospheric rheological heterogeneities on dynamic topography

Sarah Gain assisting Masters student Sean Kartun, Jean-Antoine Gazi (MRes) and Masters student Chris Corcoran using the Nu Plasma II MC-ICP-MS.

CCFS POSTGRADUATES

CCFS postgraduate students include those already in progress in 2011 with projects relevant to CCFS Research Themes, as well as those who commenced in 2012-2015. 28 papers with CCFS postgraduates as authors were published in high-profile international journals in 2015, including *Gondwana Research, Scientific Reports (Nature), Geology, Lithos, Chemical Geology, Contributions to Mineralogy and Petrology, Ore Geology Reviews, Economic Geology and Journal of Asian Earth Sciences*.
59 presentations were also given at 14 international conferences (see *Appendix 6*).

2015 HIGHLIGHTS

Cam McCuaig, Katarina Bjorkman with her award, and Nicolas Thebaud.

Katarina Bjorkman was awarded the 2015 Hammond-Nisbet Fellow Poster Award for best student poster at CET Corporate Members Day.

Beñat Oliveira Bravo attended an award ceremony in Barcelona, Spain on the 10th of April 2015 where he was officially presented with his "*La Caixa*" scholarship by Queen Letizia of Spain (*pictured below*). (http://ccaa.elpais.com/ccaa/2015/04/13/paisvasco/1428933889_198265.html)

Beñat was also awarded the Macquarie University DVC-Research Commendation PGRF award.

Chengxin Jiang was Highly Commended for "*Excellence in Higher Degree Research (Engineering, Medicine and Science)*" at the 2015 Macquarie University Research Excellence Awards.

Luis Parra-Avila received the "*David Groves Prize for Outstanding Postgraduate Research in Geology*", School of Earth and Environment, The University of Western Australia.

Vikraman Selvaraja was awarded "*Best Student Talk*" at SGA Nancy, September 2015.

Qing Xiong was nominated fo the "*Li Si-Guang Outstanding Postgraduate Award*" (Chinese national level); October 2015.

COMPLETED

Rachel Bezard (PhD): Impact of crustal assimilation on the Lesser Antilles arc lava geochemistry (MQ 2014)

Lauren Burley (MSc): The geology of the Fisher East komatiite-hosted nickel sulphide deposit (UWA 2015)

David Clark (PhD): Integrated magnetics: Contributions to improved processing and interpretation of magnetic gradient tensor data, new methods for source location and estimation of magnetisation, and predictive magnetic exploration models (MQ 2014)

Jane Collins (PhD): The structural evolution and mineralisation history of the Flying Fox komatiite-hosted Ni-Cu-PGE sulfide deposit, Forrestania Greenstone Belt, Western Australia (UWA 2013)

Cara Danis (PhD): Geothermal state of the Sydney-Gunnedah-Bowen Basin system (MQ 2012)

Tara Djokic (MPhil): Assessing the link between Earth's earliest convincing evidence of life and hydrothermal fluids: The c. 3.5 Ga Dresser Formation of the North Pole Dome, Pilbara Craton, Western Australia (UNSW 2015)

Fiona Foley (PhD): Magmatic consequences of subduction initiation and its role in continental crust formation (MQ 2013)

Yuya Gao (PhD): Origin of A-type Granites in East China: Evidence from Hf-O-Li Isotopes (MQ 2015)

Rongfeng Ge (PhD): Precambrian to Paleozoic tectono-thermal evolution in the Korla area, northern Tarim Craton, NW China (CU 2015)

Felix Genske (PhD): Assessing the heterogeneous source of the Azores mantle plume (MQ 2013)

Erin Gray (PhD): Deformation of Earth's upper mantle: insights from naturally occurring fabric types (UWA 2014)

Christopher Grose (PhD): Thermochemical models of oceanic upper mantle (MQ 2015)

Celia Guergouz (MSc): Study of the dynamic emplacement of Nickel mineralisation, as well as the geodynamics of the lithosphere (UWA/Nancy 2014)

Matthew Hill (PhD): 4D structural, magmatic and hydrothermal evolution of the Au-Cu-Bi system in the Tennant Creek Mineral Field, NT, Australia (UWA 2015)

Yosuke Hoshino (PhD): Investigation of hydrocarbon biomarkers preserved in the Fortescue Group in the Pilbara Craton, Western Australia (MQ 2015)

Jin-Xiang Huang (PhD): Origin of eclogite and pyroxenite xenoliths in kimberlites and basalts (MQ 2012)

Huiqing Huang (PhD): The petrogenesis of Jurassic granitic rocks in Western Nanling Ranges of South China and tectonic implications (CU 2013)

Carissa Isaac (PhD): 4D architecture of the Eastern Goldfields Superterrane in the Yilgarn Craton of Western Australia, in order to constrain the role of the lithospheric structure at 2.7 Ga in the localisation of nickel mineral systems (UWA 2015)

Erwann Lebrun (PhD): 4D structural modelling and hydrothermal evolution of the sediment hosted Siguiri gold deposit (Guinea) and implication on Paleoproterozoic gold targeting in West Africa (UWA 2015)

Margaux Le Vaillant (PhD): Characterisation of the nature, geometry and size of hydrothermal remobilisation of base metals and platinum group elements in magmatic nickel sulphide deposit systems. Implications for exploration targeting (UWA 2015)

Ben Li (PhD): Evolution of fluid associated with gold mineralisation in the Paleoproterozoic Granites-Tanami Orogen (UWA 2015)

Shan Li (PhD): Early Mesozoic magmatism and tectonics in the Beishan area of Inner Mongolia, China (CU 2013)

Li-Ping Liu (PhD): Timing and kinematics of Mesozoic-Cenozoic mountain building and cratonic thinning in eastern North China: a combined structural and thermochronological study (CU 2015)

Yingchao (Leo) Liu (PhD): Recognising gold mineralisation zones using GIS-Based modelling of multiple ground and airborne datasets (CU 2015)

Yongjun Lu (PhD): Controls on porphyry emplacement and Porphyry Au-Cu mineralisation along the Red River Fault, Hunan Province, China (UWA 2012)

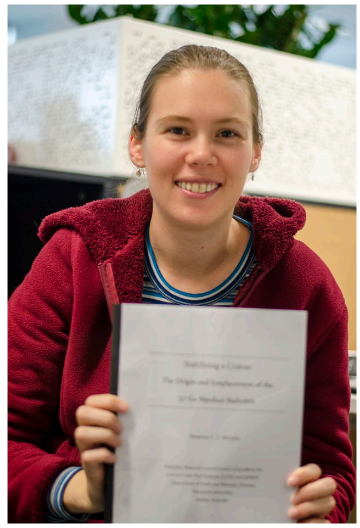
Volodymyr Lysytsyn (PhD): Mineral prospectivity analysis and quantitative resource assessments for exploration targeting-development of effective data integration models and practical applications (UWA 2015)

Jelena Markov (PhD): 3D Geophysical Interpretation of the Archean-Paleoproterozoic Boundary, Leo-Man Shield, West Africa (UWA 2015)

Kombada Mhopjeni (MSc): Investigating the Uranium potential in Namibia using GIS-based techniques (UWA 2013)

David Mole (PhD): Quantifying melt-lithosphere interaction in space and time: understanding nickel mineral systems in the Archaean Yilgarn Craton (UWA 2013)

Melissa Murphy (PhD): A novel approach for economic uranium deposit exploration and environmental studies (MQ 2013)



Rosanna Murphy (PhD): Stabilising a Craton: The Origin and Emplacement of the 3.1 Ga Mpuluzi Batholith (MQ 2015) *pictured right*

Chongjin Pang (PhD): Basin record of Mesozoic tectonic events in South China (CU 2014)

Matthew Pankhurst (PhD): Geodynamic significance of shoshonitic magmatism within the Andean Altiplano (MQ 2013)

Jonathon Poh (MSc): Numerical investigation of the driving forces of Archean fluid and heat transfer flows (UWA 2015)

Ekaterina Rubanova (PhD): Fluid processes in the deep mantle: Geochemical studies of diamonds and related minerals (MQ 2013)

James (Ed) Saunders (PhD): The nature, abundance and mobility of gold in the mantle (MQ 2014)

Elyse Schinella (PhD): Constraining the contribution of isostasy and dynamic uplift at Venusian volcanic rises and tessera terrain: implications for rifting and volcanism (MQ 2014)

Mingdao Sun (PhD): Late Mesozoic magmatism and its tectonic implication for the Jiamusi Block and adjacent areas of NE China (CU 2013)

Rajat Taneja (PhD): The origin of seamount volcanism in the Northeast Indian Ocean (MQ 2015)

Ni Tao (PhD): Thermochronological record of tectonic events in central and southeastern South China since the Mesozoic (CU 2015)

Zoja Vukmanovic (PhD): A micromechanical and geochemical analysis of remobilisation of komatiite-hosted Ni sulfide ores (UWA 2013)

Qian Wang (PhD): A geological traverse across the Jack Hills Metasedimentary Belt, Western Australia: isotopic constraints on the distribution of Proterozoic rocks and the evolution of Hadean crust (CU 2015)

Qing Xiong (PhD): Shenglikou and Zedang Peridotite Massifs, Tibet (China): Upper mantle processes and geodynamic significance (MQ 2015)

Weihua Yao (PhD): Lower Palaeozoic basin record in Southern South China: Nature of the Cathaysia basement and evolution of the Wuyi-Yunkai Orogeny (CU 2014)

Yao Yu (PhD): The evolution and water inventory of the subcontinental lithospheric mantle: A new perspective from peridotite xenoliths (SE China) and zircon megacrysts from basalts (MQ 2014)

Qingtao Zeng (PhD): Regional controls on gold mineral systems in the western Qinling Belt, Gansu Province, China (UWA 2013)

Ganyang Zhang (PhD): Sb-Au mineralisation mechanism and exploration targeting prediction research in the Northern Himalaya Metallogenetic Belt, Tibet, China (UWA 2013)

Jianwei Zi (PhD): Igneous petrogenesis and tectonic evolution of Cretaceous plutons, eastern Tibetan Plateau (UWA 2013)

Kongyang Zhu (PhD): Petrogenesis and tectonic setting of Phanerozoic granitic rocks in eastern South China (CU 2014)

CONTINUING

Constanza Jara Barra (PhD): Gold pathways: evolution of the lithospheric to crustal architecture of the El Indio Belt, Chile-Argentina (UWA, commenced 2015)

Erica Barlow (PhD): Biological evolution resulting from atmospheric and environmental change, Paleoproterozoic Turee Creek Group, Western Australia; *APA* (UNSW, commenced 2015)

Raphael Baumgartner (PhD): Ore deposits of the future; magmatic Ni-Cu-PGE sulphide mineral systems on Mars; *IPRS-A* (UWA, commenced 2013) *see Research highlight pp. 52-53*

Jason Bennett (PhD): The *in situ* microanalysis of cassiterite to constrain the genesis, evolution and geochronology of tin bearing mineralised systems; *University Postgraduate Award* (UWA, commenced 2015)

Katarina Bjorkman (PhD): 4D lithospheric evolution and controls on mineral system distribution: Insights from Marmion Terrane, Western Superior Province, Canada; *UWA SIRF-A* (UWA, commenced 2013) *see Research highlight pp. 72-73*

Richard Blake (MPhil): Organic Geochemistry of Endolithic Cyanobacteria: False biomarker signals in 2.7-2.3 Ga rocks from contamination by endolithic cyanobacteria and other organics; (UNSW, commenced 2015)

Raul Brens Jr (PhD): Origin of silicic magmas in a primitive island arc: The first integrated experimental and short-lived isotope study of the Tonga-Kermadec system; *iMQRES* (MQ, commenced 2011)

Stefano Caruso (PhD): Geological controls on the fractionation of multiple sulfur isotopes in Archean mineral systems; *SIRF & MRIWA Postgraduate Scholarship* (UWA, commenced 2015)

Montgarri Castillo Oliver (PhD): Compositional evolution of indicator minerals: Application to diamond exploration; *iMQRES Cotutelle* (MQ, commenced 2014) *see Research highlight pp. 47-48*

Mathieu Chasse (PhD): Mechanisms of Enrichment of Rare Earth Elements in Supergene Conditions; *iMQRES, COT* (MQ, commenced 2015)

David Child (PhD): Characterisation of actinide particles in the environment for nuclear safeguards using mass spectrometric techniques (MQ, part-time, submitted 2015)

Bruno Colas (PhD): Why is the San Andreas Fault so weak?; *iMQRES* (MQ, commenced 2013)

Stephen Craven (PhD): The Evolution of the Wongwibinda Metamorphic Complex, New England Orogen, NSW, Australia (MQ, part time, submitted 2015) *pictured below assisting visitor Luke Milan (University of New England) in the selFrag Lab*

Daria Czaplinska (PhD): Flow characteristics of lower crustal rocks: Field studies and numerical modelling; *iMQRES* (MQ, commenced 2012)

Greg Dering (PhD): Dynamics and emplacement mechanisms of mafic magma networks with implications for intrusion-hosted magmatic Ni-Cu-PGE sulfide deposits; *APA (CSIRO top up)* (UWA, commenced 2014) *see Research highlight p. 49*

Raphael Doutre (PhD): Spatial periodicity, self-organisation and controls on large ore deposits; *International Sponsorship, Teck Resources Ltd* (UWA, commenced 2013)

Eileen Dunkley (PhD): Hf isotopic behaviour in turbidites, migmatites and granites at Mount Stafford, central Australia; *MQRES* (MQ, part time, commenced 2010)

Timmons Erickson (PhD): Resolving the bombardment history of the early Earth using ancient zircons (CU, commenced 2013)

Katherine Farrow (PhD): *In situ* melt generation and thermal origin of the Nagadarunga Granite: Implications for the geochronology and tectonic evolution of the eastern Arunta Region, Central Australia (MQ, part time, commenced 2014)

Christopher Firth (PhD): Elucidating magmatic drivers and eruptive behaviours of persistently active volcanoes; *APA* (MQ, submitted 2015)

Denis Fougourouse (PhD): 4D geometry and genesis of the Obuasi gold deposit, Mali; *International Sponsorship* (UWA, submitted 2015)

Robyn Gardner (PhD): The nature of the lower crust: New insights from field compilations, experiments and numerical modelling; *MQRES* (MQ, commenced 2012)

Christopher Gonzalez (PhD): CO_2 devolatilisation and its influence on partial melting, subduction, and metasomatism in the mantle lithosphere; *UWA SIRF* (UWA, commenced 2012) *see Research highlight p. 40*

Louise Goode (PhD): Volcanological and geochemical evolution of East Javanese Volcanoes, Indonesia; *iMQRES (MQ, commenced 2014)*

Hadrien Henry (PhD): Fate of mafic-ultramafic domains during subduction: Modelling pyroxenite deformation, Cabo Ortegal, Spain; *iMQRES, COT* (MQ, commenced 2015) *see Research highlight pp. 37-38*

Linda Iaccheri (PhD): Petrogenesis of the plutonic rocks in the Granites-Tanami Orogen; *UWA SIRF* (UWA, commenced 2013)

Kim Jessop (PhD): Fluids and metamorphism: New insights from field mapping, metamorphic petrology and thermodynamic modelling; *APA* (MQ, commenced 2013) *pictured above*

Chengxin Jiang (PhD): Combining seismic tomography and sedimentology to understand the deep structure and evolution of the northern edge of Tibetan Plateau; *iMQRES* (MQ, submitted 2015) *see Research highlight pp. 43-44*

Jelte Keeman (PhD): Isotope characterisation of detrital zircons across the Delamerian Orogen in South Australia; *APA* (MQ, commenced 2015)

Heta Lampinen (PhD): Mineral system footprints, Edmund Basin, Capricorn Orogen, Western Australia; *SIEF* (UWA, commenced 2014) *pictured right*

Pablo Lara (PhD): Late Neoproterozoic granitoid magmatism of the southernmost section of the Dom Feliciano Belt in Uruguay: Regional geology, geochemistry, geochronology and its significance for the geotectonic evolution of the Region; *iMQRES Cotutelle* (MQ, part time, commenced 2010)

Shaijie Li (PhD): Isotopic Dating Oil Generation and Charge Events in Canning (Australia) and Sichuan (China) ; *Curtin CIPRS* (CU, commenced 2015)

Nora Liptai (PhD): Nature of the mantle beneath the Carpathian-Pannonian basin, Hungary - A mantle xenolith study; *iMQRES, COT* (MQ, commenced 2015)

Yebo Liu (PhD): Paleomagnetism of Proterozoic igneous rocks in Australia and East Antarctica: implications for pre-Pangea supercontinents and the supercontinent cycle; *Curtin CIPRS* (CU, commenced 2015) *pictured above*

Jianggu Lu (PhD): Nature and evolution of the lithospheric mantle beneath the South China block; *iMQRES Cotutelle, China Scholarship Council, iMQRES top-up* (MQ, commenced 2014)

Quentin Masurel (PhD): Controls on the genesis, geometry and location of the Sadiola-Yatela Gold Deposit, Republic of Mali; *IPRS-A* (UWA, submitted 2015)

Samuel Matthews (PhD): Tracking CO_2 sequestration using gravity gradiometry; *CO_2CRC Scholarship* (MQ, commenced 2014)

Heta Lampinen taking magnetic susceptibility measurements (photo by Heta Lampinen).

Nicole McGowan (PhD): Messages from the mantle: Geochemical investigations of ophiolitic chromites; *APA* (MQ, commenced 2012)

Keith McKenzie (PhD): Magnetic and gravity gradient tensors and the application to the analysis of remanence (MQ, commenced 2015)

Vicky Meier (PhD): Metamorphic evolution of the Kerala Khondalite belt, India; *CIPRS* (CU, commenced 2013)

Antoine Neaud (MSc): The geology of the Savannah nickel sulphide deposit, Western Australia (UWA, submitted 2015)

Jiawen Niu (MPhil): Neoproterozoic paleomagnetism of South China and implications for global geodynamics; *Curtin University ARC DP scholarship* (CU, submitted 2015)

Beñat Oliveira Bravo (PhD): Multicomponent and multiphase reactive flows in the Earth's mantle; *iMQRES, "La Caixa" Scholarship* (MQ, commenced 2013)

Luis Parra-Avila (PhD): 4D evolution of felsic magmatic suites and lithospheric architecture of the Paleoproterozoic Birimian terranes, West Africa; *IPRS, UWA SIRF, UIS, Ad Hoc Safety-Net Top-Up Scholarship, ARC Linkage project* (UWA, submitted 2015) *see Research highlight pp. 67-68*

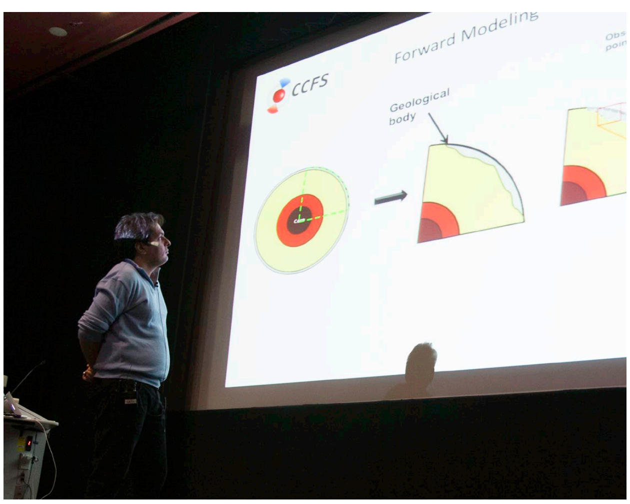
Carl Peters (PhD): Biomarkers and fluid inclusions of early Earth using samples from Australia; *iMQRES* (MQ, commenced 2013)

Greg Poole (PhD): A metallogenic model for porphyry-related and epithermal systems of the Permian-Triassic Choiyoi Group in the Cordillera Frontal, Argentina; *APA* (UWA, commenced 2015)

Shahid Ramzan (PhD): The strength of oceanic plate bounding faults; *iMQRES* (MQ, commenced 2012)

Valerie Roy (MSc): Hydrogeological and Hydrogeochemical Study of the Peak Hill-Horseshoe Deposit, Capricorn Orogen to Identify Mineral System Footprints (UWA, commenced 2014)

Farshad Salajegheh (PhD): 3D multivariable probabilistic inversion for thermochemical structure of Earth (MQ, part time, commenced 2014) *pictured below*



Vikram Selvaraja (PhD): Multi-isotopic characterisation of sulfide-bearing mineralisation in the Capricorn Orogen of Western Australia: fingerprinting ore-forming processes in space and time (UWA, commenced 2014)

Liene Spruzeniece (PhD): Fundamental link between deformation, fluids and the rates of reactions in minerals; *iMQRES* (MQ, commenced 2012)

Camilla Stark (PhD): Decoding mafic dykes in the southern Yilgarn Craton: Significance to Australia's position in supercontinent -superplume cycles; *Curtin CIPRS* (CU, commenced 2014) *pictured above*

David Stevenson (PhD): 4D modelling of the Tanami Inlier, Northern Territory (UWA, commenced 2012)

Catherine Stuart (PhD): Flow characteristics of lower crustal rocks: In depth analysis of xenoliths and experimental studies; *MQRES* (MQ, commenced 2012)

Sahand Tadbiri (MSc): The geometry and kinematics of hydrothermal veins in the c. 3.5 Ga Dresser Formation, North Pole Dome, Western Australia (UNSW, commenced 2015) *see Research highlight pp. 66-67*

Romain Tilhac (PhD): Peridotite Massifs from North-Western Iberia; *iMQRES Cotutelle* (MQ, commenced 2013) *see Research highlight pp. 37-38* *pictured above*

Mehdi Tork Qashqai (PhD): Inversion of multiple geophysical data for composition and thermal structure of Earth's upper mantle; *iMQRES* (MQ, commenced 2012)

Irina Tretiakova (PhD): The nature, extent and age of the lower crust and underlying subcontinental lithospheric mantle (SCLM) beneath the Siberian Craton (Russia); *iMQRES* (MQ, commenced 2013)

Janet Tunjic (PhD): Terranes, volcanoes and gold: relationship of gold mineralisation to stratigraphic domains and terranes in the East Yilgarn Craton, Western Australia (UWA, commenced 2014)

Yu Wang (PhD): Melting process in recycled continental crust; *iMQRES, China Science Council* (MQ, submitted 2015)

Kai Wang (PhD): Joint inversion of surface waves and body waves from ambient noise seismic interferometry; *iMQRES* (MQ, commenced 2015)

James Warren (PhD): 4D evolution of the Ora Banda and Coolgardie Domains; *RTS* (UWA, commenced 2012)

Jonathon Michael Wasiliev (PhD): Two-phase flow within the Earth's mantle: Implications for flat subduction settings; *MQRES* (MQ, commenced 2013)

Shucheng Wu (PhD): The geodynamic setting of the Western Junggar region during the Late Paleozoic: evidence from seismic tomography; *iMQRES, Cotutelle* (MQ, commenced 2015)

Jun Xie (PhD): Imaging the lithosphere structure of Australia using dispersion curve receiver functions and Rayleigh waves A/H ratio; *iMQRES Cotutelle* (MQ, commenced 2014)

Bo Xu (PhD): Mantle xenoliths and lamprophyres in Tibet: mineralisation and tectonic implications; *iMQRES Cotutelle* (MQ, commenced 2014) *pictured left*

COMMENCING 2016

Hugh Bannister (MPhil): Testing the environmental dipstick model: Carbonate compositions across the first global glaciation associated with the rise of atmospheric oxygen in Australia and South Africa (UNSW)

Tara Djokic (PhD): Visualising early life on Earth: A Virtual platform for teaching science in the modern world (UNSW)

Michael Förster (PhD): Experimental melting of rocks of ultramafic and sedimentary origin in accretionary orogens (MQ)

Uvana Meek (PhD): The curious case of the imposter cumulate, Fiordland, New Zealand (MQ)

David Silva (PhD): Spatial, temporal and metasomatic patterns in hydrous shear zones, Strangways Range, Central Australia (MQ)

PhD students at the CCFS Research Meeting held on 22-23 October 2015.

Infrastructure and technology development

CCFS links three internationally recognised concentrations of analytical geochemistry infrastructure: GEMOC's Geochemical Analysis Unit (Macquarie University) and the associated Computing Cluster, the Centre for Microscopy, Characterisation and Analysis (UWA/Curtin) and the John de Laeter Centre of Mass Spectrometry. All are nodes for the NCRIS AuScope and Characterisation Capabilities, and have complementary instrumentation and laboratories. In addition, Curtin and UWA share a leading facility for paleomagnetic studies, and facilities for experimental mineralogy and petrology are being built up at Macquarie and Curtin.

CCFS/GEMOC INFRASTRUCTURE, LABORATORIES AND INSTRUMENTATION

The analytical instrumentation and support facilities of the Macquarie University Geochemical Analysis Unit (GAU) represent a state-of-the-art geochemical facility.

The GAU contains:

- a Cameca SX-100 electron microprobe
- a Zeiss EVO MA15 Scanning electron microscope (with Oxford Instruments Aztec Synergy EDS/EBSD)
- four Agilent quadrupole ICPMS (industry collaboration; two 7500cs; two 7700cx)
- two Nu Plasma multi-collector ICPMS (one decommissioned in June 2015)
- a Nu Plasma II multi-collector ICPMS (installed in June 2015)
- a Nu Attom high resolution single-collector sector field ICPMS
- a Thermo Finnigan Triton TIMS
- three New Wave laser microprobes (one 266 nm, two 213 nm, each fitted with large format sample cells) for the MC-ICPMS and ICPMS laboratories (industry collaboration)
- two Photon Machines Excite Excimer laser ablation systems
- a Photon Analyte G2 Excimer laser ablation system
- a Photon Machines Analyte198 Femto-second laser ablation system
- a PANalytical Axios 1kW XRF with rocker-furnace sample preparation equipment
- a LECO RC412 H_2O-CO_2 analyser
- an Ortec Alpha Particle counter
- a New Wave MicroMill micro-sampling apparatus
- a ThermoFisher iN10 FTIR microscope
- a Horiba LABRAM HR Evolution confocal laser Raman microscope
- selFrag electrostatic rock disaggregation facility

Clean labs and sampling facilities provide infrastructure for ICPMS, XRF and isotopic analyses of small and/or low-level samples.

Experimental petrology laboratories include four piston-cylinder presses (pressures to 4 GPa), hydrothermal apparatus, controlled atmosphere furnaces, Griggs apparatus and a multi-anvil apparatus for pressures to 27 GPa.

THE GEMOC FACILITY FOR INTEGRATED MICROANALYSIS (FIM) AND MICRO-GIS DEVELOPMENT

GEMOC is continuing to develop a unique, world-class geochemical facility, based on *in situ* imaging and microanalysis of trace elements and isotopic ratios in minerals, rocks and fluids. The Facility for Integrated Microanalysis now consists of four different types of analytical instrument, linked by a single sample positioning and referencing system to combine spot analysis with images of spatial variations in composition ("*micro-GIS*"). The FIM has been in operation since mid-1999. Major instruments were replaced or upgraded in 2002-2004 through the $5.125 million DEST Infrastructure grant awarded to Macquarie University with the Universities of Newcastle, Sydney, Western Sydney and Wollongong as partners. Further enhancement of the facility took place following the award of an ARC LIEF grant in 2010 to integrate the two existing multi-collector inductively-coupled-plasma mass spectrometers (MC-ICPMS) with three new instruments: a femtosecond laser-ablation microprobe (LAM; installed in June 2012); a high-sensitivity magnetic-sector Nu Attom ICPMS (installed in January 2013); an Agilent 7700 quadrupole ICPMS (installed in 2010). In 2012 GEMOC was awarded ARC LIEF funding for a second generation MC-ICPMS and a Nu Plasma II was installed in June 2015.

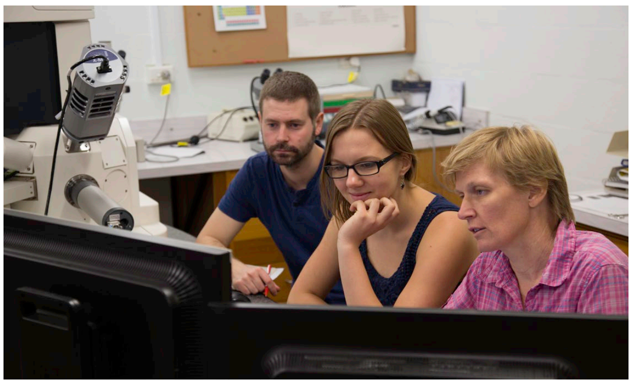
EQUIPMENT FOR HIGH-PRESSURE EXPERIMENTATION

The expansion of the high-pressure experimental facilities continued in 2015, with plans for an extension to the laboratory in a new wing extending into the yard behind building E5A. This will house two large multi-anvil presses, and a third will be installed in the current laboratory. Laser-heated diamond anvil cells and an additional piston-cylinder apparatus will be acquired in 2016 through LIEF funds from the Australian Research Council. An experimental program on electrical conductivity in mantle materials has begun with the currently available multi-anvil apparatus.

PROGRESS IN 2015:

1. Facility for Integrated Microanalysis

a. Electron Microprobe: The Zeiss EVO MA15 SEM carried the electron imaging workload providing high-resolution BSE and CL images for *TerraneChron*® (http://www.gemoc.mq.edu.au/TerraneChron.html) and other research projects, including diamonds, corundum, PGM in chromitites and experimental petrology. The Oxford Instruments AZtec Synergy combined Energy Dispersive System and Electron Back-Scatter Diffraction detector installed in 2012 provides simultaneous elemental and crystal orientation mapping. This capability has enabled new research directions in the study of deformation processes



CCFS Visiting Researcher Dr Bjarne Almqvist, Daria Czaplinska and Sandra Piazolo using the SEM to examine advanced crystallographic orientation and simultaneously acquired chemical data from New Zealand lower crustal rocks.

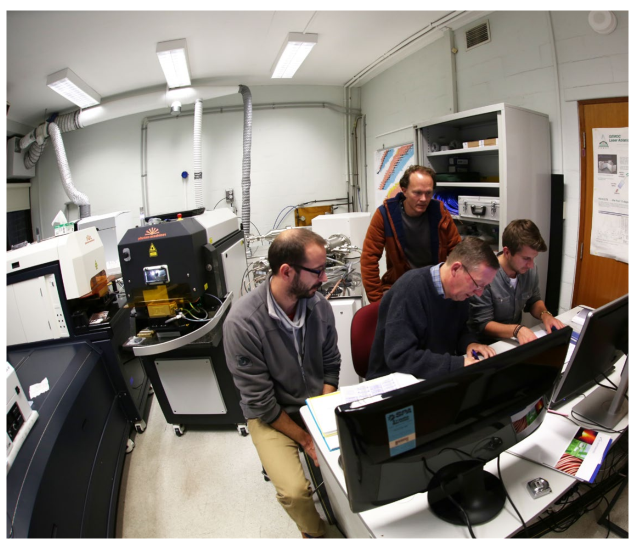
in mantle and crustal rocks, including melt/rock interaction in high-grade metamorphic rocks and metasomatism of mantle-derived peridotites, pyroxenites and chromitites. The Cameca SX100 electron microprobe (fitted with 5 wavelength dispersive spectrometers and a Bruker Energy Dispersive Spectrometer system) continued to service the demands for quantitative mineral analyses and X-ray composition maps for all projects including analysis of corundum and inclusions from kimberlitic tuffs; analysis of base metal sulfides and platinum group minerals; minor and trace element analysis of metals.

b. Laser-ablation ICPMS microprobe (LAM): In 2015 the combination of the Photon Machines G2 laser system and Agilent 7700 ICP-MS was used for all *in situ* trace element analyses and U-Pb geochronology. The facility was used by 15 Macquarie PhD thesis projects, 5 international visitors, 3 Masters Research students, 6 users from other Australian institutions and several in-house funded research projects and industry collaborations. Projects included the analysis of minerals from mantle-derived peridotites, pyroxenites and chromitites, high-grade metamorphic rocks and biominerals. U-Pb analysis of zircon was again a major activity with geochronology projects (including *TerraneChron*® applications: http://www.gemoc.mq.edu.au/TerraneChron.html) from Australia (NSW, SA, WA), New Zealand, China, Cuba, Israel, Chile, Lao People's Democratic Republic, Oman and Russia. Method development also continued for the U-Pb dating of baddelyite and rutile.

Chad Gardner, Angela Lay, Dr Ian Graham (School of BEES, UNSW) with Elena Belousova and Dr Lin Sutherland (Australian Museum & UWS) working on a collaborative project analysing trace-elements of gem stones (sapphire, ruby) and gem zircon from Australia and SE Asia.

c. MC-ICPMS: A Nu Plasma II MC-ICP-MS was installed in June 2015 and followed the decommissioning of Nu Plasma 005, after 16 years of service. Although the Nu Plasma II represents a significant advance in its electronics and engineering, much of the fundamental design is adapted from Nu Plasma I. This has enabled a relatively seamless transition of existing methods developed over the past 15 years on the Nu Plasma I. The combination of the expanded collector array (16 Faraday cups and 5 ion counters) and enhanced sensitivity compared to the first generation Nu Plasma instruments has enabled the refinement of several *in situ* techniques pioneered at GEMOC, Macquarie.

The *in situ* measurement of U-Pb isotopes in zircon using the combination of the femtosecond laser system and Nu Plasma II is a world first, and preliminary results were reported at the Goldschmidt Conference in Prague, August 2015 (*N.J. Pearson,*



The sign off for the new Nu Plasma II MC-ICP-MS - Yoann Gréau, Will Powell, Norman Pearson and Nu instrument representative Jamie Royce.

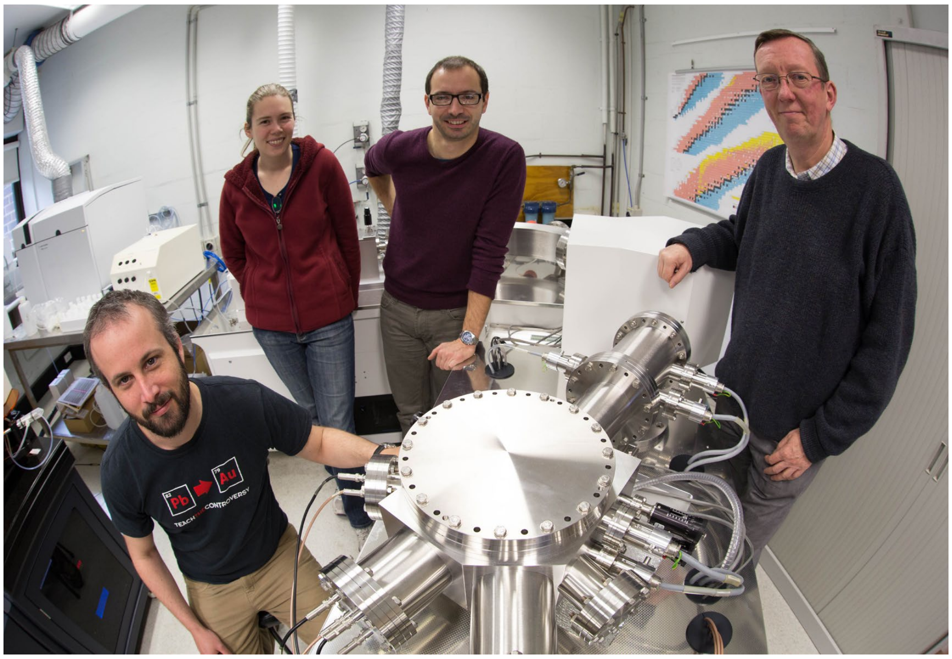
W. J. Powell, Y. Gréau, R.C. Murphy, J.L. Payne, E. Belousova, W.L. Griffin and S.Y. O'Reilly 2015. U-Pb geochronology of zircon by femtosecond laser ablation. Goldschmidt Abstracts, 2015, 2437). The development of standard operating procedures for *in situ* U-Pb, Re-Os and Rb-Sr isotope measurements is on-going. The development of Mg isotope methodologies for chromite and chromite-rich ultramafic rocks as part of the TARDIS Program (Nicole McGowan PhD) in the ARC Centre of Excellence for Core to Crust Fluid Systems (CCFS) was completed; high-precision results were obtained in wet-plasma mode on the Nu Plasma II and corroborated by replicate measurements at IGGCAS, Beijing.

At the time of the installation of the new Nu Plasma II, Nu Plasma HR 034 underwent an upgrade with an enhanced interface. The upgrade has increased sensitivity between 1.5 and 2 times, and this has contributed to an overall improvement in signal stability, as well as in the precision of single measurements and long-term reproducibility. In 2015 a third Photon Machines excimer laser microprobe was installed and co-located with Nu Plasma HR 034.

The high demand for LAM MC-ICPMS time for *in situ* high-precision ratio measurements was again led by the analysis of Lu-Hf isotopes in zircon as a major strand of the *TerraneChron*® activities (see http://www.gemoc.mq.edu.au/TerraneChron.html), with more than 1800 undertaken in 2015. *In situ* Hf isotopes were measured in zircons from Australia (NSW, WA, SA), Algeria, Bostwana, Brazil, China (Tibet), Indonesia, Iran, Israel, Laos, New Zealand, PNG and Russia. CCFS/GEMOC remains one of the few facilities with the capability to perform Re-Os dating of single grains of Fe-Ni sulfides and alloys in mantle-derived rocks. Re-Os studies were undertaken on xenoliths from eastern China, Siberia, Italy and Spain, and sulfide and platinum group minerals in chromitites from Tibet, Australia, Spain and Turkey.

d. Laboratory development: The clean-room facility established in 2004 continued to be used primarily for isotope separations for analysis on the Triton TIMS and Nu Plasma MC-ICPMS. Routine procedures have been established for Rb-Sr, Nd-Sm, Lu-Hf and Pb isotopes, as well as U-series methods (U, Th and Ra). In 2015 whole-rock Re-Os isotopic analysis of organic-rich sedimentary rocks was undertaken for the first time.

e. Software: GLITTER (GEMOC Laser ICPMS Total Trace Element Reduction) software is our on-line interactive program for quantitative trace element and isotopic analysis and features dynamically linked graphics and analysis tables. This package provides real-time interactive data reduction for LAM-ICPMS analysis, allowing inspection and evaluation of each result before the next analysis spot is chosen. GLITTER's capabilities include the on-line reduction of U-Pb data. Sales of GLITTER are handled by AccessMQ and GEMOC provides customer service and technical backup. During 2015 a further 16 full licences of GLITTER were sold bringing the total number in use to more than 235 worldwide, predominantly in Earth sciences applications but with growing usage in forensics and materials science.



GAU Director Norman Pearson (Right) acquainting the TerraneChron® Team, (L-R) Ed Saunders, Rosanna Murphy and Yoann Gréau, with the newly installed Nu Plasma II MC-ICP-MS.

Dr Will Powell continued in his role in GLITTER technical support and software development through 2015. The current GLITTER release is version 4.4.4 and is currently available without charge to existing customers and accompanies all new orders.

2. X-Ray Fluorescence Analysis

In November 2012 a PANalytical Axios 1 kW X-ray Fluorescence Spectrometer was installed and is used routinely to measure whole-rock major element compositions on fused glass discs and trace-element concentrations on pressed-powder pellets. In 2013 the sample preparation equipment was upgraded and included a new furnace to make high-quality cast glass beads. The major element calibration was modified in 2015 to extend the spectrum of rock types that could be analysed to include Fe-rich samples such as iron ores and laterites.

3. Whole-rock solution analysis

An Agilent 7500cs ICPMS produces trace-element analyses of dissolved rock samples for the projects of CCFS/GEMOC researchers and students and external users, supplementing the data from the XRF.

The ICPMS dedicated to solution analysis is also used to support the development of '*non-traditional*' stable isotopes with the refinement of separation techniques and analytical protocols (see *1. d*).

4. Diamond preparation and analysis

The GEMOC laser-cutting system (donated by Argyle diamonds in 2008) was used during 2015 to cut thin plates of single diamond crystals as part of the on-going research into diamond genesis. The plates are used for detailed spatial analysis of trace elements, isotopic ratios and the abundance and aggregation state of nitrogen. The nitrogen measurements are made using the ThermoFisher iN10 FTIR microscope, which allows the spatial mapping of whole diamond plates at high resolution with very short acquisition times using a software package developed here.

5. selFrag - a new approach to sample preparation

GEMOC's selFrag instrument was installed in May 2010 and was the first unit in Australia. This instrument uses high-powered electrical pulses to disaggregate rocks and other materials along the grain boundaries. It removes the need to crush rocks for mineral separation, and provides a higher proportion of unbroken grains of trace minerals such as zircon. Since its installation selFrag has been used for a range of applications including zircon separation, the analysis of grain size and shape in complex rocks, and the liberation of trace minerals from a range of mantle-derived and crustal rocks.

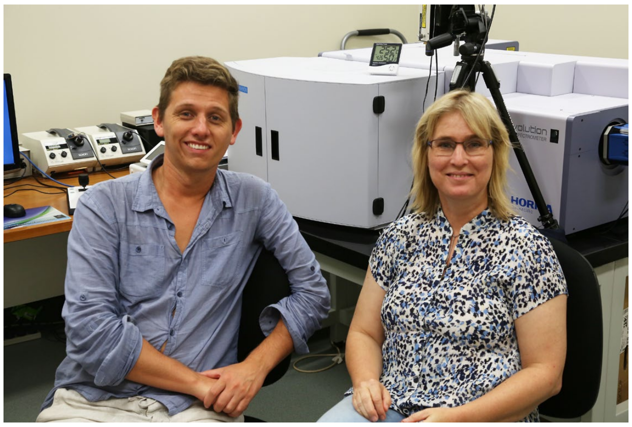
6. Spectroscopy

The spectroscopy infrastructure includes an FTIR microscope (ThermoFisher iN10 FTIR microscope; 2008). The FTIR is used to measure H abundance in a range of nominally anhydrous minerals (e.g. olivine, pyroxene, garnet) and H and N contents in diamond. In developing the spectroscopy capability an emphasis has been placed on hyperspectral mapping to produce integrated datasets and multi-layered information in a spatial context. A Horiba H-CLUE CL monochromator (MQSIS 2015) is due to be installed on the Zeiss EVO SEM in January 2016. The monochromator system will provide imaging of individual emitting species and their distribution in a sample, and provide textural evidence of crystal growth, overgrowths and replacement, deformation, diagenesis and provenance.

7. Raman spectrometry

A confocal laser Raman microscope (co-funded by MQSIS 2014 and Future Fellowship funding to A/Prof Dorrit Jacob) delivers information for non-destructive phase-identification and characterisation at one micrometre spatial resolution.

The Raman spectrometer continues to serve the CCFS, the Department and the Faculty. New acqusitions this year were a small Peltier cooled freezing stage, which is intended to help in the analysis of ephemeral phases in biominerals before they re-crystallise. In addition, the facility is now extended to include a fibre probe head, which is planned to be used for *in situ*, realtime spectrometry of high pressure experiments. George Amulele and Simon Clark are working to design and build a sample platform for this purpose, which will open up new analytical avenues for the experimental petrology group at EPS. HDR student Sophia Bratenkov and MRes student Shirin Baydjanova from the organic geochemistry group have both discovered Raman spectrometry for the characterisation of organic compounds (kerogen) in geological samples. Dr Christoph Lenz from ANSTO *(pictured below with Dorrit Jacob)* is our newest honorary associate using the instrumentation.



8. Computer cluster

The cluster Enki has continued to be a powerhouse for the geodynamics group, supporting two funded research projects, 3 PhD projects, a postdoc, and numerous Masters-level projects. Recent developments have included the development of planetary evolution capability of the mantle convection code Aspect (based on the deal.II finite element libraries), led by Siqi Zhang. In addition, O'Neill and Zhang have developed a new smoothed-particle hydrodynamic code to simulate early solar-system processes, and have been utilising Enki for these simulations. A recent RIBG round to expand the lithosphere/seismic cluster "*Toto*" was successful (led by J.C. Afonso). In addition, a GPU Tower (supplied by Xenon systems) continues to act as a development machine for GPU-capable code, including the recent SPH code, and a Xeon-Phi server (supplied by Dell) has recently been installed, enabling the modelling group to start development and migration of their codes onto this next generation hardware.

For further information on GAU facilities please consult http://ccfs.mq.edu.au/Tech/Tech.html/

CMCA TECHNOLOGY DEVELOPMENT AND INSTRUMENTATION

The University of Western Australia's Centre for Microscopy, Characterisation and Analysis (CMCA) is a $50M core facility providing analytical solutions across a diverse array of scientific research. The world-class facilities and associated technical and academic expertise are the focus of micro-analytical and characterisation activities within Western Australia, while strong links and collaborations have earned the CMCA an excellent national and international reputation. The CMCA incorporates the Western Australian Centre for Microscopy, and is a node of the NCRIS Characterisation capabilities, the National Imaging Facility (NIF) and the Australian Microscopy and Microanalysis Research Facility (AMMRF). It is also associated with the NCRIS funded Australian National Fabrication Facility (ANFF), and AuScope, which have made a substantial contribution to facilities run by CMCA.

CMCA capabilities:

- Secondary Ion Mass Spectrometry (CAMECA IMS 1280 and CAMECA NanoSIMS 50 & NanoSIMS 50L)
- Electron probe microanalysis (JEOL JXA 8530F)
- Focused ion beam (FEI Helios)
- Transmission electron microscopy (FEI Titan, JEOL 2100)
- Scanning electron microscopy (FEI Verios XHR, Zeiss 1555, Tescan Vega3)
- X-ray powder diffraction (Panalytical Empyrean)
- X-ray micro-CT (Xradia)
- Confocal Raman imaging with AFM (WiTec Alpha 300RA+)
- NMR spectroscopy (2 Bruker Avance and 2 Varian spectrometers)
- X-ray crystallography (Oxford Diffraction)
- GC and HPLC mass spectrometry
- Bioimaging, flow cytometry, cell sorting, and laser micro-dissection
- Optical and confocal microscopy
- Biological sample cryo-preparation and ultramicrotomy

THE AMMRF FLAGSHIP ION PROBE FACILITY

The CAMECA IMS 1280 and NanoSIMS 50 are flagship instruments of the AMMRF. The AMMRF Flagship Ion Probe Facility offers state-of-the-art secondary ion mass spectrometry (SIMS) capabilities to the Australian and international research communities, allowing *in situ*, high-precision isotopic and elemental analyses, and secondary ion imaging on a wide range of samples.

The IMS 1280 large-geometry ion probe, installed in 2009, was co-funded by the University, the State Government of Western Australia, and the Federal Government's Department of Innovation, Industry, Science and Research (DIISR) under the "*Characterisation*" (AMMRF) and "*Structure and Evolution of the Australian Continent*" (AuScope) capabilities of the National Collaborative Research Infrastructure Strategy (NCRIS). The NanoSIMS 50, installed in 2003, was funded through the Federal Government's NCRIS-precursor, the Major National Research Facility scheme (NANO-MNRF). CMCA is also a part of the National Resources Science Precinct's (NRSP) Advanced Resources Characterisation Facility (ARCF).

The Ion Probe Facility is a key characterisation component within the ARC Centre of Excellence for Core to Crust Fluid Systems. To ensure the highest levels of quality and throughput, the CCFS has provided funding for a Research Associate position within the Ion Probe Facility, to facilitate direct scientific and technical interaction for all CCFS users and projects.

The Ion Probe Facility is also a member of the International Atomic Energy Agency's (IAEA) Network of Analytical Laboratories (NWAL), performing U isotope analyses on environmental samples for Nuclear Safeguards.

The CMCA's NanoSIMS 50 being lowered into the new laboratory.

PROGRESS IN 2015:

In 2015, the CMCA installed a new CAMECA NanoSIMS 50L ion probe as part of the NRSP's Advanced Resources Characterisation Facility (ARCF). The ARCF provides multiscale characterisation capabilities for Geoscience research, from the scale of drill core down to the atom scale. The Facility, funded through CSIRO's Science and Industry Endowment Fund (SIEF), features the Geoscience Atom Probe recently installed in the John de Laeter Centre at Curtin University, and the synchrotron-less MAIA mapping facility under development at CSIRO. The NanoSIMS 50L represents a considerable technological advance over the existing NanoSIMS 50, with a seven-FC/EM multicollector array and a new oxygen ion source allowing high-resolution isotope measurements on geological samples. UWA contributed around $1M to build a new state-of-the-art laboratory to house both NanoSIMS instruments, and two new full-time positions.

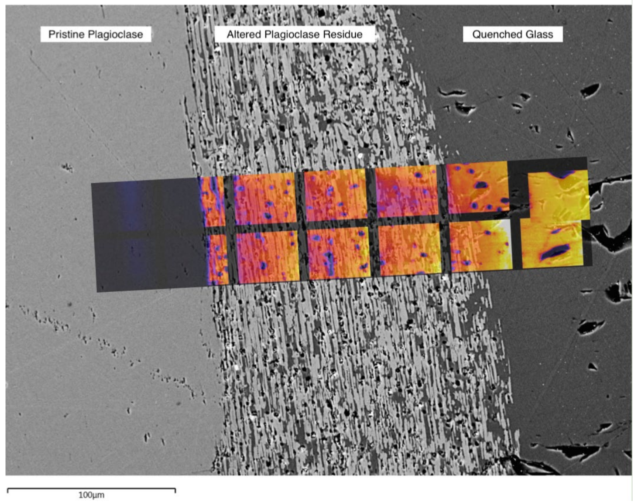
Recent successes in ARC LIEF funding have also updated the electron microscopy facilities at CMCA, with the installation in late 2015 of a FEI Helios Focused ion beam (FIB) platform. The dual-beam instrument allows ion beam milling of samples for TEM, NanoSIMS and Atom Probe analysis, and high-resolution 3D imaging.

2015 saw some personnel changes in the SIMS team at CMCA. Heejin Jeon joined the IMS1280 lab, and Haibo Jiang joined the NanoSIMS lab. Heejin is a geologist and SIMS expert with experience with both IMS1280 and SHRIMP. She completed her PhD at ANU, and then spent a 2-year research position at the NORDSIM facility in Stockholm (see her full profile on *p. 12*). Haibo completed his PhD in materials science at the University of Oxford, developing NanoSIMS applications for a wide range of projects.

The Ion Probe Facility has continued to contribute to various projects in the context of CCFS. The IMS1280 clocked up almost 4000 hours, across more than 20 projects. The majority of work involved multiple S isotope analyses with CET colleagues (Fiorentini, LaFlamme, Selveraja, Caruso), and O isotopes in zircon (Iaccheri, Bjorkman, Lu, Kirkland).

High-precision isotope measurement with SIMS requires calibration against known standards to correct for instrumental mass fractionation between analysis sessions. This varies significantly between different materials, such that each new material analysed by SIMS necessitates the development of new standards. 2015 saw a big push to develop in-house standards for a range of sulfide minerals - pyrite, pyrrhotite, pentlandite, chalcopyrite, and arsenopyrite. The results have been submitted for publication.

In 2015 the CMCA once again played an important role in a wide range of cross-nodal CCFS collaborative projects. The CCFS pilot project "*Making the Invisible Visible*", involving the NanoSIMS to image isotope labels in experimental samples, began in earnest. UWA Honours students Jack Adams and Haydn White visited Macquarie to perform experiments under the tutelage of Sandra Piazolo, Tracey Rushmer and John Adam, returning to UWA to perform the NanoSIMS analysis. Macquarie PhD student Liene Spruzeniece also visited the NanoSIMS lab to image experiments performed in Germany.



Isotope labels: The image shows the reaction interface between a plagioclase feldspar crystal on the left and hydrous silicate melt on the right. The SEM shows two sharp boundaries between the unreacted crystal, the reaction zone, and the melt. The overlain NanoSIMS image shows the oxygen isotopic composition across the reaction zone, and reveals that the reaction zone is enriched in ^{18}O from the melt.

CMCA-CCFS 2015 publications: were published in high profile Journals such as *Precambrian Research, Lithos, Geology Contributions to Mineralogy and Petrology, and Earth and Planetary Science Letters*: CCFS Publications #380a, 489, 519, 527, 601, 742, 751, 771

For further information on CMCA facilities please consult http://www.cmca.uwa.edu.au/

CCFS COO Magdalene Wong Borgefjord and Matt Kilburn viewing the newly installed CAMECA NanoSIMS 50L ion probe.

JOHN DE LAETER CENTRE

The John de Laeter Centre (JdLC) is a collaborative research venture involving Curtin University, the University of Western Australia, CSIRO and the Geological Survey of Western Australia.

It hosts over $28M in infrastructure supporting research in: geosciences (geochronology, thermochronology and isotope studies); environmental science; isotope metrology; forensic science; economic geology (minerals and petroleum); marine science; and nuclear science.

The mission of the Centre is to *"build world-class research infrastructure in Western Australia for the benefit of Earth, Environment and Materials Science research"*. The JdLC is headquartered in the Faculty of Science and Engineering at Curtin University, but has a governing board consisting of members of the joint venture partners as well as representatives from the mining, petroleum and environment sectors.

The Centre experienced rapid growth in 2015 through the merger of mass spectrometry and microscopy facilities at Curtin, the commissioning of $5,200,000 in new analytical instrumentation and the appointment of 4 new research fellows. A new website has been developed to provide detailed information on the new facilities, instrumentation and research staff (http://www.jdlc.edu.au).

The components of the JDLC are organised into fourteen major facilities:

A key milestone in 2015 was the establishment of the **(GAP) Geoscience Atom Probe Facility** as a node of the Advanced Resources Characterisation Facility (ARCF) funded by a $12,400,000 Science and Industry Endowment Fund grant to Curtin, UWA and CSIRO. The GAP hosts a Cameca LEAP 4000X HR microscope (*pictured below*) capable of carrying out atom probe tomography (APT), a new characterisation technique combining high spatial resolution with time-of-flight mass spectrometry to provide 3-dimensional chemical information at the atomic scale. More commonly used to study semiconductors and metal alloys, the GAP is the first atom probe facility in the world to be dedicated to the study of geological materials (http://www.geoscienceatomprobe.org). The facility also commissioned a Tescan Lyra focused ion beam scanning electron microscope (FIB-SEM), with a Ga+ gun capable of micro-milling out a 100 nm wide needle of mineral sample prior to APT analysis. The Lyra system is a highly advanced platform for 2D and 3D microanalysis with time of flight mass spectrometry (TOF-SIMS) and electron back scattered diffraction (EBSD) detectors. By correlating the analytical outputs of both the LEAP and the Lyra instruments, the ARCF provides an unprecedented capability of characterising highly complex materials on a wide range of length scales.

The JdLC also commissioned a new **(DMH) Digital Mineralogy Hub Facility** with grant funding from the Australian Research Council supported by Curtin University, University of Western Australia, Murdoch University and the Geological Survey of Western Australia. The Facility hosts a Tescan Integrated Mineral Analyzer (TIMA GM) - a fully automated, high throughput, analytical Field Emission Gun Scanning Electron Microscope (FEGSEM) for automated analysis of sample composition. TIMA measures mineral abundance, liberation properties, mineral association and grain size automatically on multiple samples of grain mounts, thin sections or polished sections. Applications include ore characterisation, process optimisation, remediation and the search for precious metals and strategic elements. The facility is being used by a broad spectrum of researchers: geologists and archeologists are using the facility in petrological characterisation, sample classification and lithofacies studies; while geochemists and geochronologists are using the mineral classification outputs as targeting maps for further ion, electron or laser microprobe analysis. An automated mineralogy workshop held at Curtin in November 2015 attracted 25 participants from the local minerals and petroleum services industry.

(CEG) Curtin Experimental Geochemistry Facility:

CEG provides facility for experimental petrology, geochemistry and hydrogeochemistry at pressures and temperatures that range from those at the Earth's surface to those at the base of the Earth's crust. The Facility contains:

- 2 x 150 ton end loaded piston cylinder presses
- Coretest hydrothermal apparatus
- Assorted furnaces to 1400 degrees C
- Assorted titanium and Teflon-lined bombs

The Cameca LEAP 4000X HR microscope.

(GHF) GeoHistory Facility:

The GHF houses state-of-the-art laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS) equipment, in addition to a low temperature thermochronology laboratory. The LA-ICPMS comprises a Resonetics S-155-LR 193nm excimer laser ablation system coupled to an Agilent 7700x quadrupole ICPMS. The Excimer laser is also coupled to a RESOchron helium analysis line for *in situ* (U-Th-Sm)/He, U-Pb and trace element analysis of single crystals. The facility also has a separate Alphachron helium line with a diode laser and furnace in order to facilitate conventional (U-Th)/He dating on single mineral crystals and larger samples. In late 2015 a Nu Plasma II multi-collector will be integrated into the facility to facilitate split stream analysis.

(MMF) Microscopy and Microanalysis Facility:

The MMF houses a broad range of advanced microanalysis instrumentation providing high quality chemical, mineralogical and microstructural information, and high resolution images for research and technical publications. The facility staff have expertise in Materials and Earth Science research which is used to support both academic research and applied projects for the Western Australian minerals and energy sector. Techniques and instrumentation available include:

- High resolution imaging (SEM, TEM) - The EVO is a variable pressure scanning electron microscope (VP-SEM). The microscope is suitable for general purpose microstructural analysis at high vacuum, or for the analysis of non-conductive/hydrated samples at lower vacuum.

  The JEM is a transmission electron microscope (TEM) with a LaB6 filament. The TEM is equipped with an EDS detector and a scanning TEM attachment. This instrument is capable of elemental and microstructural analysis at extremely high magnifications.
- Spatially resolved elemental analysis (EDS) and Phase & orientation analysis (EBSD) - The MIRA3 is a variable pressure field emission scanning electron microscope (VP-FESEM) that features sensitive EDS and EBSD detectors and integrated software for high quality microstructural analysis of crystalline samples.
- Quantitative mineral analysis (Q-XRD) - The D8A is an X-ray Diffractometer (XRD) with a copper X-ray source and an automated 45 position sample changer. It features a LynxEye position sensitive detector that is 200 times faster than a conventional scintillator detector, allowing collection of superior data in a short time-frame.
- Ion beam sample manipulation including TEM & TKD lamella preparation (FIB) - The NEON is a dual beam focused ion beam scanning electron microscope (FIB-SEM) equipped with a field emission gun and a liquid metal Ga+ ion source. This instrument combines high resolution imaging with precision ion beam ablation of focused regions, allowing for site specific analysis of the surface and subsurface of samples in 2D or 3D.

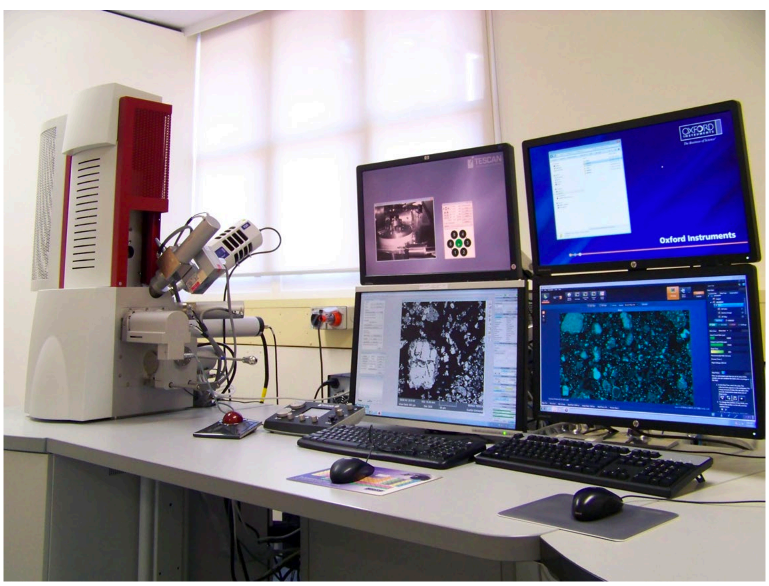
The MMF also houses a suite of equipment that includes light microscopy, vacuum mount impregnation, manual and automated polishers, mills and coaters that are used to prepare samples for electron microscopy and X-ray diffraction.

(SAXS) Small Angle X-Ray Scattering Facility:

The small angle X-ray scattering can be used to characterise the size, shape and distribution of objects between 1 and 100 nm. Instrumentation includes a Bruker NANOSTAR SAXS comprising a copper sealed tube X-ray source with a gas filled two dimensional photon counting detector. 2015 LIEF funding will be used to upgrade the instrumentation in the facility.

(SHRIMP) Sensitive High Resolution Ion Micro Probe Facility:

The facility at Curtin has two automated SHRIMP II ion microprobes capable of 24-hour operation, together with a preparation laboratory that was remodelled in 2014. The equipment allows *in situ* isotopic analysis of chemically complex materials with a spatial resolution of 5-20 microns. The main application of the SHRIMP instruments at Curtin is for U-Th-Pb geochronology of zircon and other U-bearing minerals, including monazite, xenotime, titanite, allanite, rutile, apatite, baddeleyite, cassiterite, perovskite and uraninite where multiple growth zones commonly require analyses with high spatial resolution. SHRIMP II is fitted with a Cs source, electron gun and 5 channel M/C. SHRIMP II A is currently being developed for stable isotope analysis of O in zircon and other silicates, and S in sulfides.



The MIRA3 (http://jdlc.edu.au/microscopy-and-microanalysis-facility-mmf/).

(SMS) selFrag & Mineral Separation Facility:
A selFrag facility, supported by an ARC LIEF grant, has been installed within the Department of Applied Geology at Curtin University. The facility provides electric pulse disaggregation for mineral separation, which allows mineral grains to be separated from rock samples without the damage associated with standard crushing techniques.

(TIMS) Thermal Ionisation Mass Spectrometry Facility:
The TIMS facility at Curtin incorporates a Thermo Finnegan *Triton*™ and a VG 354 multicollector mass spectrometer. The Triton is equipped with a 21-sample turret and 9 faraday cups, enabling a precision of 0.001% on isotopic ratios. As well as geological applications within the broad field of isotope geochemistry (Re/Os, U/ Pb, Pb/Pb, Sm/Nd, Rb/Sr) the TIMS instruments can be applied to a variety of isotope fingerprinting, such as forensics and the environmental impact of human activities. The TIMS instruments are also used for the calibration of isotopic standards and the calculation of isotopic abundances and atomic weights. The facility has recently installed a Thermo Scientific *Triton*™ mass spectrometer, facilitating a new range of geochemical, geological and environmental research applications.

(TRACE) Trace Research Advanced Clean Environment Facility:
This consists of a ~400 m^2 class 1000 containment space housing four class 10 ultra-clean laboratories, a class 10 reagent preparation laboratory and a –18 °C class 10 cold clean laboratory, located at Curtin University. The extremely low ultimate particle counts are achieved with successive '*spaces within spaces*' and HEPA filtration at each stage.

(WAAIF) Western Australian Argon Isotope Facility:
This is located at Curtin and is equipped with A MAP215-50 mass spectrometer with a low-blank automated extraction system coupled with a New Wave Nd-YAG dual IR (1064 nm) and UV (216 nm) laser, an electromultiplier detector and Niers source. The ultra-violet laser is capable of high-resolution (up to 10 µm beam size) ablation of any mineral, allowing detailed analysis of individual mineral grains. The facility also houses an Argus VI Multi-Collector Noble Gas Mass Spectrometer.

The $^{40}Ar/^{39}Ar$ method is used to date a myriad of geological events such as volcanism, tectonic plate movements, mountain building rates, sediment formation, weathering and erosion, hydrothermal fluid movements, and alteration and diagenesis of minerals.

(WA-OIG) WA Organic and Isotope Geochemistry Facility:
WA-OIG is an internationally-recognised group contributing to world-class research in the fields of organic and stable isotope geochemistry; palaeogenomics and geomicrobiology. Available techniques are listed here: http://jdlc.edu.au/wa-organic-and-isotope-geochemistry-facility-wa-oig/.

(WABC) The West Australian Biogeochemistry Centre:
The WABC is a centralised, stable isotope facility housed at UWA. The Centre brings together a critical mass of researchers in stable isotope science, particularly in its application to environmental and ecological problems in both terrestrial and marine environments. The following instrumentation is available:

- Automated Nitrogen Carbon Analyser with Isotope Ratio Mass Spectrometer
- SerCon Elemental Analyser (Gas Solid / Liquid Preparation Unit), coupled with:
  - 20-22 Stable Isotope Ratio Mass Spectrometer (Sercon, Crewe UK)
- Picarro Cavity Ring-down Spectrometer L1115-I
- Delta XL Isotope Ratio Mass Spectrometer (Thermo/ Germany) connected with:
  - GasBench II (GB)
  - Thermal Conversion /Elemental Analyser (TC/EA)
- Delta V Plus Isotope Ratio Mass Spectrometer (Thermo / Germany) connected with:
  - Thermo Elemental Analyser Flush 1112 via Conflo IV
  - Finnigan LC-IsoLink
- Agilent 6890/5973B GC-MSD

(XSAF) X-Ray Surface Analysis Facility:
The Western Australian XSAF provides access to a state of the art X-ray photoelectron spectroscopy system for studying surface elemental and chemical composition. X-ray photoelectron spectroscopy (XPS) is a non-destructive technique used to probe the elemental and chemical composition of the first 2-5 nm of a sample surface. All elements heavier than helium can be detected down to an atomic concentration of 0.1-1%. The primary instrument in the facility is the Kratos AXIS Ultra DLD X-ray photoelectron spectroscopy system with imaging hemispherical analyser, monochromated Al and Ag X-ray sources, Ag/Mg X-ray flood source, argon gas cluster ion gun, field emission electron source and ultra-violet helium lamp.

For further information on JDLC facilities please consult http://www.jdlc.edu.au

WESTERN AUSTRALIA PALEOMAGNETIC AND ROCK-MAGNETIC FACILITY

The Western Australia Paleomagnetic and Rock-magnetic Facility was established at the University of Western Australia by CCFS CI Z.X. Li in 1990, funded by a UWA start-up grant to the late Professor Chris Powell. It was subsequently upgraded through an ARC Large Instrument Grant in 1993 to purchase a then state-of-the-art 2G Enterprises AC-SQUID cryogenic magnetometer and ancillary demagnetisation and rock magnetic instruments. It was upgraded again in 2006 with a 4k DC SQUID system plus a Variable Field Translation Balance (VFTB) through an ARC LIEF grant, into a regional facility jointly operated by Curtin University, UWA and the Geological Survey of WA. A MFK-1FB kappa bridge was installed in 2011. In 2014, a national consortium consisting of Curtin University, The University of Western Australia, the Australian National University, Macquarie University and University of Queensland was awarded an ARC LIEF grant to purchase a new 2G 755 superconducting rock magnetometer with a vertical Model 855 automated sample handler (the RAPID system) and other accessories (ovens etc.), to be housed in a purpose-built magnetically shielded room at Curtin University's Bentley campus. The magnetically shielded room was constructed during July-August 2015 by Dr Gary Scot's team, and the laboratory refurbishment is expected to be completed in February 2016. The newly purchased AGICO JR-6A spinner magnetometer and a TD-48SC thermal demagnetiser are already serving the research group, and delivery of the 2G RAPID system is expected in mid-2016. Dr Josh Beardmore has recently been appointed as the Technical Officer who will oversee the day-to-day operation of the facility from 2016.

The joint WA facility is one of three similar laboratories in Australia. The new purchases will build on existing instruments in the facility, including:

- a 2G 755 superconducting rock magnetometer with a vertical Model 855 automated sample handler (the RAPID system) and other accessories
- 755 2G cryogenic magnetometer upgraded (LE0668377) to a 4K DC SQUID system (currently back to 2G for a minor upgrade and for repair of the lightning-damaged cold head)
- MMTD80, MMTD18 and TD-48-SC thermodemagnetisers
- Variable Field Translation Balance (VFTB)
- MFK-1FB kappabridge
- Bartington susceptibility meter MS2 with MS2W furnace

A wide range of research topics has been investigated using the facility, including reconstructing the configuration and drifting history of continents all over the world from the Precambrian to the present, analysing regional and local structures and deformation histories, dating sedimentary rocks and thermal/chemical (e.g. mineralisation) events, orienting rock cores from drill-holes, tracing ancient latitude changes, paleoclimates, and recent environmental pollution.

There are four major current research programs for the updated facility:

(1) Supercontinent studies

(2) Formation and evolution of the Australian continent

(3) Magnetostratigraphy and applications to petroleum geology and palaeoclimatic studies

(4) Planetary science applications and the early Earth

Industry interaction

INDUSTRY INTERACTION AND TECHNOLOGY TRANSFER ACTIVITIES

CCFS has a strategic goal to interact closely with the mineral exploration industry at both the research and the teaching/training levels. The research results of the Centre's work are transferred to industry and to the scientific community in several ways:

- collaborative industry-supported Honours, MSc and PhD projects
- short courses relevant to industry and government-sector users, designed to communicate and transfer new technologies, techniques and knowledge in the discipline areas relevant to CCFS
- one-on-one research collaborations and shorter-term collaborative research on industry problems involving national and international partners
- provision of high-quality geochemical analyses with value-added interpretations on a collaborative research basis with industry and government organisations, extending our industry interface
- use of consultancies and collaborative industry projects (through the commercial arms of the national universities) which employ and disseminate the technological and conceptual developments carried out by the Centre
- GLITTER, an on-line data-reduction program for Laser Ablation ICPMS analysis, developed by GEMOC and CSIRO/GEMOC participants, has been successfully commercialised and continues to be available from GEMOC through Access MQ (http://www.gemoc.mq.edu.au/); the software is continually upgraded
- collaborative relationships with technology manufacturers (more detail in the section on "*Infrastructure and technology development*")

The Centre for Exploration Targeting (CET) at UWA (http://www.cet.edu.au/industry-linkage) provides CCFS with a unique interface with a broad spectrum of mineral exploration companies and many CET activities (e.g. research projects, workshops and postgraduate short courses).

CCFS supports the national UNCOVER initiative:

http:/www.uncoverminerals.org.au/)

SUPPORT SOURCES

CCFS industry support includes:

- direct funding of research programs
- industry subscriptions (CET)
- '*in kind*' funding including field support (Australia and overseas), access to proprietary databases, sample collections, digital datasets and support for GIS platforms
- logistical support for fieldwork for postgraduate projects
- collaborative research programs through ARC Linkage Projects and the University External Collaborative Grants (e.g. Macquarie's Enterprise Grant Scheme) and PhD program support
- assistance in the implementation of GIS technology in postgraduate programs
- participation of industry colleagues as guest lecturers in undergraduate units
- extended visits by industry personnel for interaction and research
- ongoing informal provision of advice and formal input as members of the Advisory Board

ACTIVITIES IN 2015

- *TerraneChron*® studies (see *p. 95* and http://www.gemoc.mq.edu.au/TerraneChron.html) have enjoyed continued uptake by a significant segment of the global mineral exploration industry. This methodology, currently unique to CCFS/GEMOC, requires the integration of data from three instruments (electron microprobe, LAM-ICPMS and LAM-MC-ICPMS) and delivers fast, cost-effective information on the tectonic history of regional terranes (http://www.gemoc.mq.edu.au/TerraneChron.html). The unique extensive database (over 30,000 zircon U-Pb and Hf-isotope analyses) in the Macquarie laboratory allows unparalleled contextual information in the interpretations and reports provided to industry. Four major Industry Reports were completed for collaborative industry projects related to *TerraneChron*® at CCFS/GEMOC in 2015. This formally involved project collaboration with four industry partners.
- The Distal Footprints of Giant Ore Systems: UNCOVER Australia, (supported by CSIRO ex Science & Industry Endowment Fund (SIEF), MERIWA and industry collaborators) continued. The project aims to develop a toolkit with a workflow to identify the distal footprints of the Giant Ore Systems in order to overcome the fundamental limitation in

current exploration methodologies; Australia's thick cover of weathered rock and sediment.

- The ARC Linkage Project titled "*Global Lithosphere Architecture Mapping*" (GLAM) was extended as the "*LAMP*" (Lithosphere Architecture Mapping in Phanerozoic orogens) project through a Macquarie University Enterprise Grant with Minerals Targeting International as the external industry partner. A sub-licencing agreement with Minerals Targeting International accommodates Dr Graham Begg's role and access to GLAM IP (in relationship to Macquarie, BHP Billiton and the GLAM project) as Director of this company. Dr Begg spent significant research time at GEMOC through 2015 as part of the close collaborative working pattern for this project.
- On-going collaboration with BHP Billiton (Dr Kathy Ehrig) and University of Tasmania (Professor Vadim Kamenetsky) looking for evidence of younger magmatic events (e.g. Grenville-age events) in the magmatic evolution of the Gawler Craton, with a particular focus on the region around the giant Olympic Dam deposit.
- A collaborative project funded by Rio Tinto Limited commenced in 2014. Marco Fiorentini and Yongjun Lu (UWA) are investigating "*The mineral chemistry of zircon as a pathfinder for magmatic-hydrothermal copper and gold systems*". The project aligns with the goals of Flagship Program 2, Genesis, transfer and focus of fluids and metals.
- GEMOC's development of a methodology for analysis of trace elements in diamond continued to open up potential further developments and applications relevant to industry, ranging from diamond fingerprinting for a range of purposes to improving the knowledge framework for diamond exploration. This work is continuing, with a focus on understanding the growth and chemical history of individual diamonds and diamond populations. It was supported in 2015 by CCFS Flagship Program 1.
- The GEMOC technique for dating the intrusion of kimberlites and lamproites using LAM-ICPMS U-Pb analysis of groundmass perovskite continued. This rapid, low-cost application has proven very attractive to the diamond exploration industry, and has led to several collaborative projects.
- Geodynamic modelling capabilities have now been extended to industry-related projects. An ongoing collaboration between GEMOC and Granite Power Ltd has led to important data exchange, and to a paper (*CCFS publication #165*) on the thermal and gravity structure of the Sydney Basin.
- A continuing collaborative relationship with New South Wales Geological Survey is applying *TerraneChron*® to investigations of the provenance of targeted sequences in the Paleozoic sedimentary terranes of eastern Australia, and the development of the Macquarie Arc and the Thompson Orogen.
- A collaborative research project continued in 2015 with the GSWA as a formal CCFS Flagship Program, in which GEMOC is carrying out *in situ* Hf-isotope analyses of previously SHRIMP-dated zircon grains from across the state. This is a part of the WA Government's Exploration Incentive Scheme.
- Following Professor Bill Griffin's Noumea workshop on new approaches to exploration and minor-element exploitation in ophiolitic complexes, a collaborative project was established with Jervois Mining, involving a co-tutelle PhD student (Matthieu Chasse) jointly supervised by Professor George Callas, Pierre et Marie Curie University, Paris, France. This project continued in 2015.
- CET held their annual "*Corporate Members Day*" on the 8th of December 2015, to showcase its research to its Corporate Members. The day provided an audience of over 65 representatives from CET Member companies with the opportunity to discuss the innovative work of the CET, including its involvement in CCFS, and also gave the CCFS ECR and postgraduate students a chance to interact with industry (http://www.cet.edu.au/industry-linkage). Posters and poster presentations by CET staff and students showcased the width and breadth of research activities. CCFS PhD Student, Katarina Bjorkman was awarded the Hammond-Nisbet Fellow Poster Award for best student poster (see *p. 77*).
- Industry visitors spent varying periods at Macquarie, Curtin and UWA (CET) in 2015 to discuss our research and technology development (see visitor list, *Appendix 7*). This face-to-face interaction has proved highly effective both for CCFS researchers and industry colleagues.
- DIATREEM (an AccessMQ Project) continued to provide LAM-ICPMS analyses of garnets and chromites to the diamond-exploration industry on a collaborative basis.
- CCFS publications, preprints and non-proprietary reports are available on request for industry libraries.
- CCFS participants were prominent in delivering keynote and invited talks and workshop modules, and convening sessions relevant to mineral exploration at national and international industry peak conferences in 2015 (see Abstracts, *Appendix 6*).

A full list of previous GEMOC publications is available at http://www.GEMOC.mq.edu.au

TerraneChron®

A new tool for regional exploration for minerals and petroleum

GEMOC CCFS

- ✓ Based on zircon analyses
- ✓ Efficient and cost-effective
- ✓ Identifies regional tectonic events
- ✓ Dates magmatic episodes
- ✓ Fingerprints crust reworking and mantle input (fertility)

Contact: Elena Belousova, Bill Griffin or Suzanne O'Reilly
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MACQUARIE University

What is *TerraneChron*®?

The methodology was developed by GEMOC to provide rapid, cost-effective characterisation of crustal history on regional (10-1000 km^2) scales. It is based on U-Pb, Hf-isotope and trace-element analysis of single zircon grains by laser-ablation ICPMS (single- and multi-collector) methods.

- U-Pb ages, with precision equivalent to SHRIMP
- Hf isotopes trace magma sources (crustal vs juvenile mantle input)
- Trace elements identify parental rock types of detrital zircons

What kind of samples?

- Regional heavy-mineral sampling (modern drainages: terrane analysis)
- Sedimentary rocks (basin analysis)
- Igneous rocks (dating, specialised genetic studies)

Applications to mineral exploration

- Rapid assessment of the geology in difficult or poorly mapped terrains
- "Event Signatures" for comparison of crustal histories from different areas
- Identify presence/absence of key rock types (eg Cu/Au porphyries, A-type granites….)
- Prioritisation of target areas

Applications to oil and gas exploration

In provenance studies, the information from Hf isotopes and trace elements provides a more detailed source signature than U-Pb ages alone.

- *TerraneChron*® defines the crustal history of the source region of the sediment
- Changes in direction of basin filling track regional tilting, subsidence
- Stratigraphic markers in thick non-fossiliferous sediment packages
- Proven applications in the North Sea

CURRENT INDUSTRY-FUNDED COLLABORATIVE RESEARCH PROJECTS

These are brief descriptions of current CCFS projects that have direct cash support from industry, most with combinations from ARC, internal University or State Government support. Projects are both national and global. In addition to these formal projects, many shorter projects are directly funded by industry, and the results of these feed into our basic research databases (with varied confidentiality considerations). Such projects are administered by the commercial arms of the relevant universities (e.g. AccessMQ Limited, at Macquarie).

CCFS industry collaborative projects are designed to develop the strategic and applied aspects of the basic research programs, and many are based on understanding the architecture of the lithosphere and the nature of Earth's geodynamic processes that have controlled the evolution of the lithosphere and its important discontinuities. Basic research strands translated to strategic applications include the use of geochemical data integrated with tectonic analyses and large-scale datasets (including geophysical) to understand the relationship between lithosphere domains and large-scale mineralisation. The use of sulfides to date mantle events, and the characterisation of crustal terrane development using U-Pb dating and Hf isotopic compositions of zircons (*TerraneChron*®) are being developed as a regional isotopic mapping tools for integration with geophysical modelling.

CCFS PROJECTS FUNDED BY INDUSTRY (INCLUDING ARC LINKAGE)

Reducing 3D geological uncertainty via improved data interpretation methods	***Linkage Project*** ***Industry Collaborators: Western Mining Services Australia Pty Ltd, Geological Survey of Western Australia*** ***CIs: Jessell, Holden, Baddeley, Kovesi, Ailleres, Wedge, Lindsay, Gessner, Hronsky*** ***Summary:*** The integrity of 3D geological models heavily relies on robust and consistent data interpretation. This project proposes an innovative workflow for 3D modelling to minimise geological uncertainty. Advanced visualisation and intelligent decision support methods will be combined to assist geological interpretation. Feedback on interpretation will be provided based on data evidence and consistency with expert knowledge and previous interpretations. The process can be considered as a spelling and grammar checker for geological interpretation. The outcome of this study aims to achieve an improved workflow that reduces model uncertainty, resulting in a broad and significant impact on the management of Australian mineral, energy and water resources.
Craton modification and growth: the east Albany-Fraser Orogen in three-dimensions	***Linkage Project*** ***Industry Collaborator: Geological Survey of Western Australia*** ***CIs: Tkalcic, Kennett, Spaggiari, Gessner*** ***Summary:*** The objective of this work is to achieve new, synergistic techniques for delineating the three-dimensional structure of the east Albany-Fraser Orogen in Western Australia, and the lithospheric structure below it. These methods will guide understanding of the potential for mineral resources in this region with little surface geological exposure.
Chronostratigraphic and tectonothermal history of the northern Capricorn Orogen: constructing a geological framework for understanding mineral systems	***Linkage Project*** ***Industry Collaborator: Geological Survey of Western Australia*** ***CIs: Rasmussen, Dunkley, Muhling, Johnson, Thorne, Korhonen, Kirkland, Wingate*** ***Summary:*** The application of innovative age dating techniques with field mapping and a new deep seismic survey across the Capricorn Orogen by this project will help construct a vastly improved geological framework for understanding large mineral systems. Outcomes of this project will reduce uncertainty and risk in exploration, thereby improving the discovery rate of natural resources.

Gold pathways: evolution of the lithospheric to crustal architecture of the El Indio Belt, Chile-Argentina	***Industry Collaborator: Barrick Exploration (finance and logistical support)*** ***CIs: McCuaig, Jara-Barra*** ***Summary:*** This study will test the Mineral System hypothesis in one of the most highly Au-endowed provinces of the Andes Cordillera (>40 Moz Au), intending to define: the trans-lithospheric architecture that acts as the magma/fluids pathway, linking the fertile source with the deposits' location; and this architecture's geodynamic evolution related to metallogenic events. The El Indio Belt has a long exploration history, providing a broad variety of studies and datasets (geophysical, geochemical, geological) on which this work will build. The study will provide the first regional syntheses of these datasets, complemented with new field, isotopic and structural data.
Enhanced predictive capability for targeting high quality magmatic hydrothermal copper, gold and molybdenum deposits	***Industry Collaborator: Rio Tinto Exploration*** ***CIs: Fiorentini, Lu, Loucks, McCuaig*** ***Summary:*** Zircon chemistry has great potential to be used as a pathfinder for porphyry Cu ± Mo ± Au systems. We will examine a large integrated LA-ICP-MS U-Pb age and trace element dataset for both infertile and ore-productive magmatic suites to elucidate distinctive zircon signatures diagnostic of metallogenic fertility of the parent magma. This dataset will provide a relevant boost in the exploration kit arsenal of porphyry explorers, both at the detection and predictive scale. There will be significant potential for translation of this knowledge into ongoing exploration campaigns that utilise the detrital record as the primary means of sample analysis.
The distal footprints of giant ore systems: UNCOVER Australia	***Supported by CSIRO ex Science & Industry Endowment Fund (SIEF)*** ***Industry Collaborator: CSIRO, University of Western Australia, Curtin University, Geological Survey of Western Australia*** ***CIs: Hough, Reddy, McCuaig, Tyler, Dentith, Shragge, Miller, Fiorentini, Aitken*** ***Summary:*** Australia is an old continent with much of its remaining mineral wealth masked by a thick cover of weathered rock and sediments that pose a formidable challenge for future mineral exploration. This project aims to develop a toolkit with a workflow to identify the distal footprints of the Giant Ore Systems to address a fundamental limitation in current exploration methodologies.
Lithospheric architecture mapping in Phanerozoic orogens	***Industry Collaborator: Minerals Targeting International (PI G. Begg)*** ***CIs: Griffin, O'Reilly, Pearson, Belousova, Natapov*** ***Summary:*** The GEMOC Key Centre has developed the conceptual and technological tools required to map the architecture and evolution of the upper lithosphere (0-250 km depth) of cratons (the ancient nuclei of continents). Through two industry-funded programs we have mapped most of the world's cratons, making up ca 70% of Earth's surface. The remaining 30% consists of younger mobile belts, which hold many major ore deposits, but are much more complex and difficult to map. This pilot project is developing the additional tools required to map the mobile belts.
Multiscale dynamics of hydrothermal mineral systems	***Supported by MERIWA*** ***Industry Collaborators: Integra Mining, First Quantum Minerals, AngloGold Ashanti, SIPA Resources, GSWA, Newmont, Goldfields, Barrick Gold, OZ Minerals*** ***CIs: Ord, Gorczyk, Gessner, Hobbs, Micklethwaite*** ***Summary:*** The project aims to produce an integrated framework for the origin of giant hydrothermal deposits. The study crosses all the length scales from lithospheric down to thin section. The goal is to define measurable parameters that control the size of such systems and that can be used as mineral exploration criteria. In particular the emphasis is on: (i) criteria that distinguish a '*successful*' from a '*failed*' mineral system and (ii) vectors to mineralisation within a successful system.

International links in CCFS

BACKGROUND

CCFS' International links provide leverage of intellectual and financial resources on a global scale, and an international network for postgraduate experience. International Partners provide the core of such collaborations. Other international activity includes funded projects and substantial collaborative programs with major exchange-visit programs in France, Norway, Germany, United Kingdom, New Zealand, Canada, USA, Taiwan, Italy, Spain, South Africa, South America, China, Brazil, Mexico, Japan, Thailand and Russia.

FORMAL MEMORANDA OF UNDERSTANDING (MOU)

Formal MOU between international institutions promote the Centre's collaborative research and facilitate visits by Centre staff and postgraduates as well as joint PhD research projects. CCFS has agreements with the following international institutions:

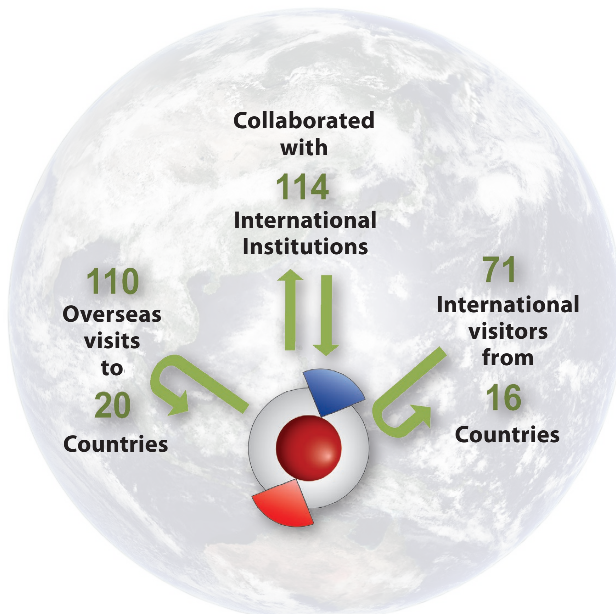
- China University of Geosciences (Wuhan) - 2011 (& Cotutelle)
- Constitution of the International University Consortium in Earth Science - 2012
- University of Science and Technology of China, Hefei - 2012 (& Cotutelle)
- Institute of Geology and Geophysics, China University of Geosciences (Beijing) - 2014
- Institute of Tibetan Plateau Research, CAS (Beijing) - 2014
- Helmholtz Centre Potsdam GFZ German Research Centre for Geosciences, Germany - 2015

COTUTELLE MOU

Cotutelle MOU aim to establish deep, continuing relationships with international research universities through joint research candidate supervision. CCFS has agreements with the following international institutions:

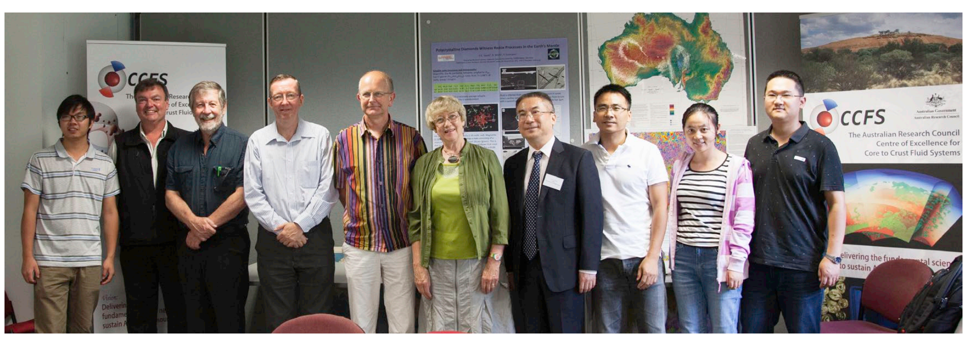
- China University of Petroleum, Beijing, China
- Durham University, United Kingdom
- Eötvös Loránd University, Hungary
- Friedrich-Alexander-University of Erlangen, Nuremberg, Germany
- Institute of Geology and Geophysics, Chinese Academy of Sciences, China
- Nanjing University, China
- Peking University, China
- Universidad de la Republica, Uruguay
- Université Montpellier 2, France
- Université Paul Sabatier, France
- University Jean Monnet, France
- University of Barcelona, Spain
- University of Zaragoza, Spain

2015 COLLABORATIVE ACTIVITY



INTERNATIONAL LINKS - 2015 HIGHLIGHTS

- A formal Memorandum of Understanding was signed with the Helmholtz Centre Potsdam GFZ German Research Centre for Geosciences, Germany



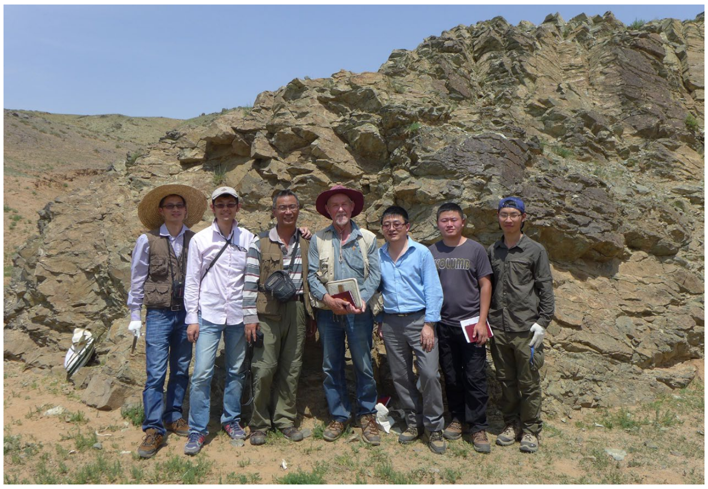
Visitors from China University of Geosciences (Wuhan) meeting with mebers of the MQ FSE Faculty and CCFS.

CCFS members meeting with representatives from the China University of Geosciences (Wuhan).

- Delegates from several International Institutions visited CCFS in 2015 to discuss programs including the exchange of staff, joint research activities and the exchange of students. Cotutelle workshop visitors from China University of Geosciences (Wuhan) and delegates from China University of Geosciences (Beijing) met with CCFS and toured the GAU facilities.
- Two representatives from Universidad Tecnológica del Uruguay (UTEC) and National Agency for Research and Innovation (ANII), Dr Rodolfo Silveira, President, Technological Laboratory of Uruguay (LATU) and Advisor, Universidad Tecnológica del Uruguay (UTEC) and Ms María Laura Fernandez, Head of International Cooperation, National Agency for Research and Innovation (ANII) met with members of CCFS to discuss developing international programs, research and international strategies, industry partnerships and to seek collaborations in areas of mutual interest.
- Professor Zheng Xiang Li (*pictutred below centre)* conducted the first ACTER (Australia-China Joint Research Centre for Tectonics and Earth Resources; http://tectonics.curtin.edu.au) annual field workshop from the 2nd to the 11th of March 2015, with the theme of the "*Tectonic History of the South China Block and Approaches for Tectonic Analysis*".

ACTER is a joint research centre led by the Institute for Geoscience Research at Curtin University, and the Institute of Geology and Geophysics of the Chinese Academy of Sciences, and participated in by key collaborating institutions from the two countries.

ACTER aims to facilitate: collaborative research and research training in geotectonics and mineral and hydrocarbon resources, the exchange of staff and joint supervision of research students, shared access to analytical facilities, organise joint conferences and annual focused field-based workshops and the exchange of academic materials and information.



Former CCFS PhD students Chongjin Pang and Shan Li (far left), together with Profs Jianbo Zhou (Jilin University) and Simon Wilde and Xuan-Ce Wang (CCFS) and two PhD students from Jilin University, undertaking fieldwork in the Solonker-Xar Moron shear zone of Inner Mongolia.

- CCFS participants attended a collaborative two-week field trip in July to the Central Asian Orogenic Belt (CAOB) of Inner Mongolia. The Fieldtrip was jointly funded by Xuan-Ce Wang's ARC Future Fellowship and the National Key Basic Research Program of China and a NNSF grant to Prof Jian-Bo Zhou. The field trip aimed to understand the petrogenesis of Paleozoic mafic and felsic rocks of the Xing-Meng Orogenic Belt and their geodynamic processes, to investigate the major sutures that mark the final closure of the Paleo-Asian Ocean and to test if the Solonker suture zone really is the main suture. Participants included Dr Xuan-Ce Wang and Professor Simon Wilde from Curtin, Prof J. Zhou and his team from Jilin University, PhD student Y. Wang from Peking University, and Dr Chongjin Pang from Guilin University of Technology (*pictured above*).
- Professor Simon Wilde visited the University of Campinas (UNICAMP), Sao Paulo, Brazil from 29 July to 10 August to discuss future collaborative projects and undertake fieldwork in the Sao Francisco Craton with Prof Elson Oliveira and colleagues. The visit was supported by a Scientific Cooperation Agreement between ATN 2014 and FAPESP.

The joint project runs from October 2104 to September 2016 and involves three themes: (a) dating the deposition age of sedimentary rocks (b) using geochronology to determine the precise timing of ore body formation and (c) dating high-grade rocks in the Sao Francisco Craton. The project evolved through long-standing collaboration between Elson Oliveira and Neal McNaughton.

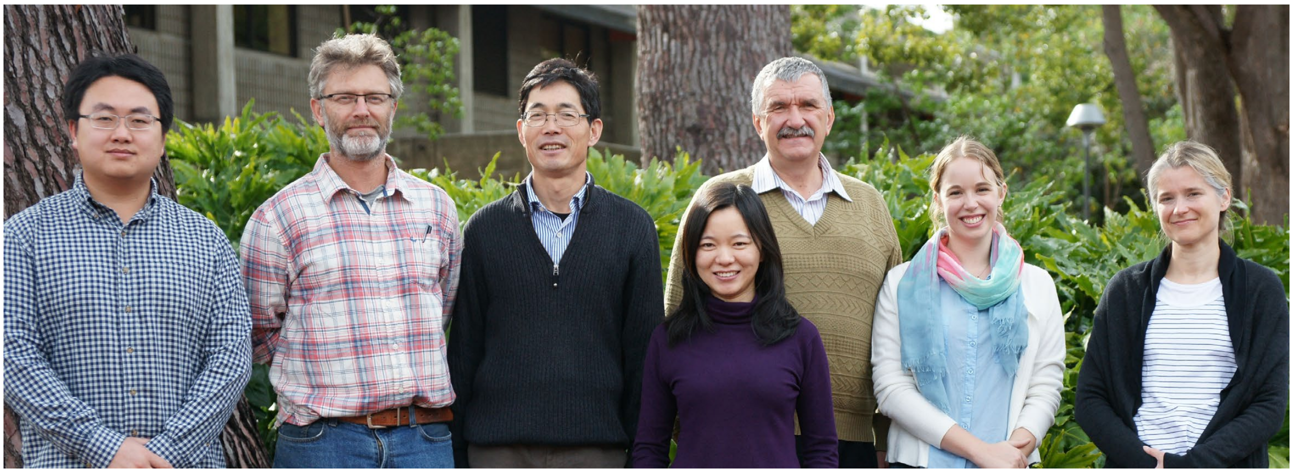
- Dr Xuan-Ce Wang from Curtin, Prof Wu-Xian Li from CAS, Dr Chongjin Pang from Guilin University of Technology and two PhD students from CAS participated in a ten-day field trip to the Zhejiang and Jiangxi provinces, China. The field trip was jointly funded by Xuan-Ce Wang's ARC Future Fellowship and collaborating Chinese partners and aimed to investigate the formation of the Neoproterozoic rift basin in South China, in particular the tectonic setting of mafic and associated sedimentary rocks.
- Several field sessions related to the TARDIS Program were conducted in Tibet In 2015:
  - 2-13 July; Bill Griffin, Ming Zhang, Jin-Xiang Huang and Qing Xiong, together with colleagues from the Tibetan Plateau Research Institute (CAS, Beijing) as part of the CCFS TARDIS-II Program.
  - 5 July to 29 August; Bo Xu. Bo is affiliated with the group of Prof Zeng-Qian Hou (CAGS), and this work is part of the TARDIS-II Program.


Tibet.

- Associate Professor Kelsie Dadd, a member of the ANZIC (IODP) Governing Council, took part in a field trip to observe the geology of the Himalayas in Tibet. The field trip was associated with the Second Post-Cruise meeting following IODP Exp 349 to the South China Sea and led by Xixi Zhao of Tongji University in Shanghai.


Kelsie Dadd at the Qomolangma (Mt Everest) Base Camp at 5,200 m.

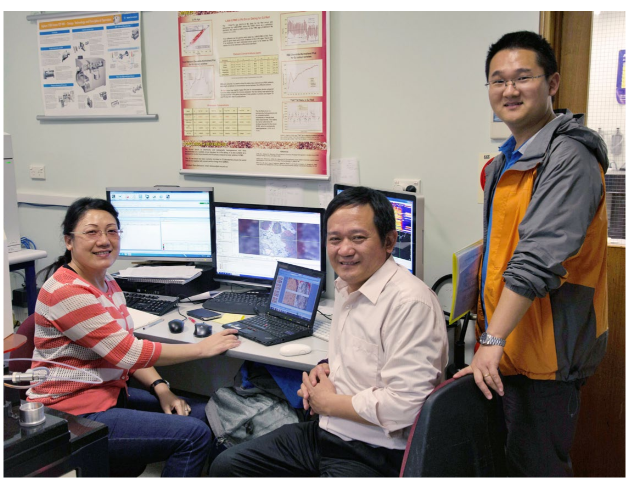
- Dr Weihua Yao visited Chengdu, China in October for 16 days fieldwork as part of a collaborative research grant with the China Geological Survey (Chengdu).
- Professor Bill Griffin visited Norway to discuss Norwegian eclogite localities with geologist Johannes Vik Seljebotn and Togeir Garmo (*pictured p. 101*), Norway's foremost mineral collector, and to plan a joint CCFS-China University of Geosciences (Wuhan) field workshop to be run in the Western Gneiss Region in 2016.



Members from Flagship Program 5. L-R: Yebo Liu (PhD student), Galen Halverson (CCFS visitor from McGill University), Zheng-Xiang Li, Weihua Yao, Sergei Pisarevsky, Sarah Chamberlain (Honours student), and Camilla Stark (PhD student). (photo Zheng-Xiang Li)

Bill Griffin discussing Norwegian eclogite localities with geologist Johannes Vik Seljebotn and Togeir Garmo.

- Professor Qin-Yan Wang (petrologist *pictured below left*) and Professor Yi-Xian Xu (geophysicist, *pictured below centre*) visited CCFS in 2015 from the China University of Geosciences (Wuhan). They analysed trace-elements of garnet, with the help of Dr Qing Xiong.



- Associate Professor Galen Halverson *(pictured above)* from McGill University, Montreal, Canada visited Zheng Xiang Li and members of CCFS Flagship Program 5 at Curtin on study leave to work on Neoproterozoic global palaeogeography, basaltic weathering and palaeoclimate

CCFS fosters many of its international links through visits by collaborators to undertake defined short-term projects, or short-term visits to give lectures and seminar sessions.

International visitors are listed in Appendix 7.

CCFS funding

Financial accounting for allocated funds is carried out at each node. MQ is responsible for the final reporting to ARC through the DVC Research, and is audited through the Macquarie University process.

STRATEGY FOR CCFS FUNDING LEVERAGE

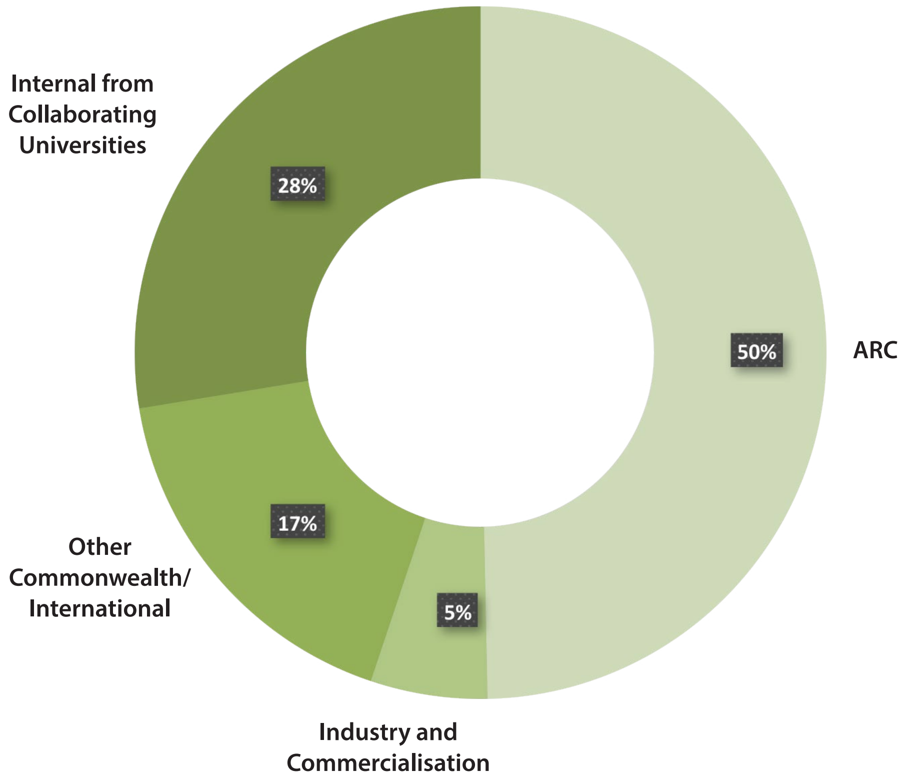
ARC anticipates that Centres of Excellence will develop a profile of basic and strategic research outcomes that provides an attractor for leveraging resources. Active strategies within CCFS include:

- Collaborative project building with industry partners
- Applications to funding schemes for matching funds for new infrastructure purchases and partner co-investment
- Technology development to deliver new and improved methodologies and tools for enhanced research collaboration and for the exploration industry
- Diversification of the funding portfolio to include other Government schemes, industry and participation in international research programs
- Applications to relevant ARC funding schemes for projects not funded from the ARC CCFS allocation, but aligned with CCFS goals
- Providing input into future NCRIS (especially AuScope) policies, using CCFS research concentration and leading directions to inform national priorities

This is an unaudited summary of 2015 income and expenditure. A full, audited statement of detailed expenditure and income is prepared by Macquarie University. No in-kind support is included here.

CCFS Income & Expenditure Statement 2011-2015						
Source	**2011**	**2012**	**2013**	**2014**	**2015**	**2016 Forecast**
Income						
ARC	$1,828,350	$2,004,179	$1,971,746	$2,031,333	$1,952,842	$2,020,500
MQ	$626,705	$1,032,004	$1,822,748	$1,464,360	$1,925,076	$968,500
UWA	$133,500	$763,500	$415,000	$415,000	$453,539	$415,000
Curtin	$727,725	$608,055	$851,244	$611,290	$523,292	$500,000
GSWA	$150,000	$150,000	$150,000	$150,000	$150,000	$150,000
SLF Income	$500,000					
SLF interest	$13,744	$12,530	$5,790	$1,811	$336	$200
ECR Income from ARC	$1,250,000					
ECR Interest		$24,734	$16,118	$6,566	$1,841	$1,000
TOTAL INCOME	**$5,230,024**	**$4,595,003**	**$5,232,646**	**$4,680,360**	**$5,006,926**	**$4,054,000**
ACCUMULATED FUNDS FROM PREVIOUS YEAR		$3,702,071	$4,960,194	$5,181,390	$4,776,770	$4,378,094
Expenditure						
Salary	$783,390	$1,608,470	$2,263,183	$2,402,327	$2,423,825	$2,739,182
Equipment	$90,128	$220,548	$785,851	$512,413	$93,008	$1,060,172
Travel	$91,305	$280,795	$388,431	$404,572	$440,158	$390,110
Maintenance/Consumables	$42,433	$459,530	$487,255	$494,580	$640,889	$642,654
Scholarship	$520,697	$767,538	$1,086,730	$1,271,088	$1,807,722	$533,000
TOTAL EXPENDITURE	**$1,527,952**	**$3,336,880**	**$5,011,450**	**$5,084,980**	**$5,405,602**	**$5,365,118**
ACCUMULATED FUNDS	$3,702,071	$4,960,194	$5,181,390	$4,776,770	$4,378,093	$3,068,176

INCOME SOURCES 2015



National Benefit

- Scientific innovation relevant to National Priority Areas

  Research Priority 1: An Environmentally Sustainable Australia

  Goal 1: Water - a Critical Resource

  Goal 2: Transforming existing industries

  Goal 6: Developing Deep Earth Resources

  Research Priority 3: Frontier Technologies for Building and Transforming Australian Industries

  Goal 1: Breakthrough Sciences

  Goal 2: Frontier Technologies

- Enhanced international links
- Excellence in training of our future generation of geoscientists
- Enhanced industry links nationally and internationally
- Improved exploration tools and strategies for Australian mineral exploration companies both on- and off-shore
- Technological innovation (scientific advances, intellectual property, commercialisation, value-added consulting services
- Implementation of significant parts of the UNCOVER initiative set out in: "*Searching the deep earth: a vision for exploration geoscience in Australia*" published by the Australian Academy of Science (2012; https://www.science.org.au/supporting-science/science-sector-analysis/reports-and-publications/searching-deep-earth-vision). CCFS addresses initiatives (ii) - (iii): investigating Australia's lithospheric architecture, 4D geodynamic and metallogenic evolution, and distal footprints of ore deposits.

Appendix 1: Flagship Programs aims and progress for 2015

1. TARDIS II: DEEP-EARTH FLUIDS IN SUBDUCTION ZONES, OPHIOLITES AND CRATONIC ROOTS

Themes 1, 2 and 3, Early Earth, Earth's Evolution and Earth Today, contributing to understanding Earth's Architecture and Fluid Fluxes.

AIMS

This program investigates aspects of deep subduction during continental collision, ophiolite fragments that get caught up in the subduction environment, and the role of fluids in the deep mantle and lithosphere. Super-reducing, ultra-high-pressure (SuR-UHP: 400-600 km) mineral assemblages in selected ophiolites carry implications for the evolution of fluid compositions, reactions and redox states in subduction environments from the surface to the Transition Zone, and suggest a new geodynamic collision process that may improve mineral exploration concepts for paleosubduction regimes. The recent discovery of similar ultra-reduced mineral assemblages in ejecta from Cretaceous volcanoes in Israel suggests a previously unrecognised process of interaction between deep-mantle fluids and ascending basaltic magmas. We aim to determine the extent of isotopic fractionation in a range of elements caused by redox reactions that produce many oxygen-free phases at UHP conditions. Goals are to produce an experimentally testable model for the generation and preservation of highly reducing conditions in the mantle, to quantify constraints on the geochemical and tectonic processes that have produced SuR-UHP assemblages, and to produce a geodynamic model for these processes.

UHP rocks, lithospheric diamonds and the Israeli volcanics will be used to refine the geochemical signatures of deep fluids and microstructural histories to provide additional insights into deep-mantle fluid types and processes. The isotopic variability of carbon, oxygen, nitrogen and sulfur in diamond-forming fluids will be studied to ascertain whether these are primary signatures, or are produced by isotopic fractionation during diamond growth.

2015 Report

Several major studies of ophiolitic chromitites were finished and are published or in press, defining a model for generation of chromitites by magma mixing, new ideas for the mechanisms of PGM inclusions in chromites, and the behaviour of chromitites and PGMs during thermal and regional metamorphism and deformation.

A comprehensive investigation of microstructures and mineralogy in Tibetan ophiolites has defined their evolution, including formation in ancient SCLM within subduction-zone settings, followed by subduction into the upper transition zone and exhumation to the sea floor prior to final emplacement by thrusting during continental collision.

Detailed isotopic and geochemical studies provided evidence that the diamonds found in Tibetan and Uralian ophiolites represent a previously unrecognised environment of diamond formation, and not anthropogenic contamination.

Studies of zircons in Australian and Tibetan ophiolites produced strong evidence that the zircons and other crustal minerals are introduced into the peridotites of the ophiolites during emplacement into the crust, and are not part of the mantle. Detailed method development allowed demonstration that extreme isotopic fraction of Li in zircon is related to late diffusion.

Techniques were developed for the *in situ* analysis of Si and C isotopes in SiC (moissanite) by SIMS, allowing a new evaluation of the formation environment of SiC in the mantle.

Ed Saunders' work has put new constraints on the abundance, residence and mobility of Au in the mantle. Mathieu Chasse has begun a project on the behaviour of Scandium in lateritic weathering profiles on mafic-ultramafic rocks.

Petrological studies on the Cabo Ortegal complex (Portugal) are building up a picture of the rarely-seen sub-arc mantle and its mafic rocks.

A number of xenolith studies added new data allowing improvement of a comprehensive picture of the deep crust and upper mantle beneath the North China Craton and other parts of Asia, as well as the Pannonian Basin.

Studies of ejecta (corundum aggregates) from Israeli volcanoes identified a suite of highly reduced phases, implying the mixing

Corundum (including sapphires and rubies) ready for polishing to examine inclusions, trace elements and isotopes.

of deep-mantle fluids (dominated by $CH_4 + H_2$) with mafic magmas.

See *Research highlights pp. 37-38, 39, 53-55, 63-64, 70-71*

Published outputs for 2015

CCFS Publications: #348, 502, 519, 522, 523, 607, 525, 532, 533, 591, 593, 610, 611, 614, 622, 631, 640, 647, 650, 651, 653, 654, 673, 674, 678, 690

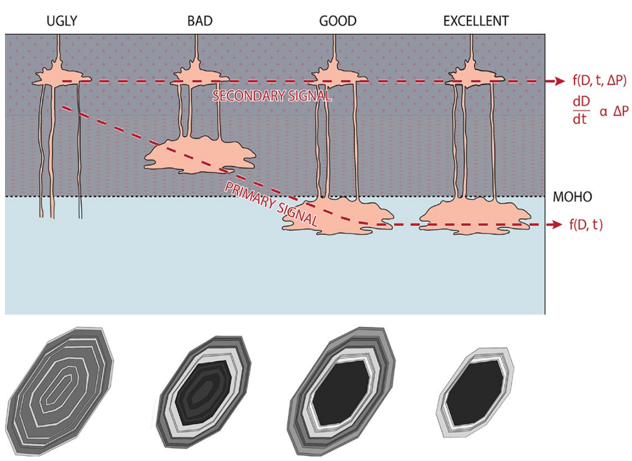
22 Conference Abstracts

2. MULTI-SCALE FOUR-DIMENSIONAL GENESIS, TRANSFER AND FOCUS OF FLUIDS AND METALS

Themes 2 and 3, Earth's Evolution and Earth Today, contributing to understanding Earth's Fluid Fluxes.

AIMS

This program takes on a holistic approach to ore deposit research, acknowledging that the genesis of mineral occurrences required the conjunction in time and space of three main independent parameters, including fertility, lithosphere-scale architecture, and favourable transient geodynamics. In this context, this study tests the hypothesis that the genesis of sizeable mineral deposits is the end product of self-organised critical systems operating from the scale of the planet all the way to the very focused environment where ore deposits can form. The principal aim is to address the critical link between metal source fertility and four-dimensional evolution of multi-scale fluid pathways that ensure efficient mass and fluid flux transfer between the mantle and the upper crust.



Schematic showing four end member scenarios in the subduction-related porphyry mineral system framework. According to the lithospheric architecture and geodynamic setting of any specific scenario, and depending upon the relative efficiency of differentiation and volatile-saturation processes, these systems may either evolve towards the formation of barren porphyries or to the creation of world-class mineralised camps. Most importantly, the zircon grains crystallising from magmatic systems that underwent these different processes in a range of tectono-stratigraphic settings may have distinct morphological, chemical and isotopic characteristics. These may be preserved in the detrital record and be useful in targeting high quality magmatic-hydrothermal copper, gold and molybdenum deposits.

2015 Report

Progress in 2015 has been formidable, with steady advances in the 3 Modules that make up the framework of the Flagship Program.

Module 1 (Fertility) included (1) studies focused on the Thrym Complex of southeastern Greenland and on the Ivrea Zone of northwest Italy to unravel the transport mechanisms of volatiles and metals in the lithosphere, and (2) studies to improve our understanding of the emplacement dynamics of mineralised porphyry systems, which showed that zircon can discriminate between metallogenically fertile and infertile arc igneous complexes and intra-plate granitoids. Module 2 (Architecture) has focused on three key areas that display significant metal endowment in both Archean and Proterozoic terranes: western Superior Craton, West Africa Craton and North Australia Craton. The project in the Western Superior Craton, which is the main focus of the PhD project of Katarina Bjorkman, will successfully conclude in late 2016, with the delivery of an isotopic map that displays the 4D evolution of the Wabigoon Terrane. In the North Australia Craton (NAC), the PhD project of David Stevenson (completing late 2016) targeted undiscovered mineralised regions under cover within the NAC and employed the methods generated during this study to elucidate architectural controls on mineralisation within covered terranes globally. The PhD project of Linda Iaccheri (completing late 2016) focused on generating new oxygen and Hf isotope compositions of detrital zircons from 1.8 Ga turbidites from the North Australia Craton. In the West Africa Craton, the study focused on unravelling the geodynamic and mineral system evolution through a systematic lithostratigraphic compilation throughout the various investigated terranes. Finally, outcomes from Module 3 (Transient Geodynamics) provided a solid foundation for a better understanding of host rock rheology on the emplacement dynamics of mantle derived magmas, and the variable geometries of the intrusions that are observed in nature.

See *Research highlights pp. 45, 49, 57, 62, 68, 72-73, 74-75*

Published outputs for 2015

CCFS Publications: #463, 508, 531, 587, 592, 616, 620, 630, 639, 644, 657, 660, 682, 686

9 Conference Abstracts

3. TWO-PHASE REACTIVE FLOW IN MULTI-COMPONENT DEFORMABLE MEDIA

Themes 2 and 3, Earth's Evolution and Earth Today, contributing to understanding Earth's Architecture and Fluid Fluxes.

AIMS

The overarching goal of this program is the development and application of in-house state-of-the-art computational simulation tools to model complex geochemical-geodynamic processes involving two-phase reactive flow in multi-component deformable media. Many aspects of Earth Science, from ore deposits to giant earthquakes, depend critically on the complex interaction of solids and fluids. Numerical simulation of these processes and effective visualisations of the results is critical to understanding how these Earth system components work, but our ability to do this is currently very limited. Flagship Program 3 is developing the next generation of numerical codes and refining thermodynamic parameters by high-pressure experiments to handle these complex problems. This will lead to important improvements in the quantification and visualisation of Earth processes, and will be applied to a variety of geodynamic situations. The new experimental group at Macquarie joins this initiative to provide input on physico-chemical parameters of minerals and fluids in the deep mantle, the composition of melts that infiltrate the lithosphere, and their effects on its geodynamics and stability.

2015 Report

This year saw the development of full global, high resolution runs with a modified version of the code *"Aspect"*. We have also completed coding and testing of melting, devolatisation and melt depletion of the mantle. Our first papers with the new global models have been published (*CCFS Publication #675*), illustrating the effect of evolving planetary systems on core evolution.

A refined method for handling multiphase/component flow has been developed and benchmarked, and the technique was published by Oliveira et al. (*CCFS Publication #685*). An efficient algorithm for implementing thermodynamic information into geophysical inversions and geodynamic simulations has been completed (*CCFS Publication #668*). A true two-phase multicomponent reactive flow numerical framework was successfully completed in 2015 and presented at the Workshop "*From Foundations to State-of-the-Art in Magma/Mantle Dynamics*" in Cambridge in 2016.

A 3-D crustal and upper mantle S-wave velocity model of northeastern China is being constructed using inversion of phase velocity dispersion curves at 6–140 s periods from ambient noise tomography and two-plane surface wave tomography. Built upon the observed velocity anomalies, we propose a sub-lithosphere mantle convection model for northeastern China. This work is published in *CCFS Publication #578*.

The expansion of the high-pressure experimental facilities continued in 2015, with plans for an extension to the laboratory in a new wing. This will house two large multi-anvil presses, and a third will be installed in the current laboratory. Laser-heated diamond anvil cells and an additional piston-cylinder apparatus will be acquired in 2016 through LIEF funds from the Australian Research Council. An experimental program on electrical conductivity in mantle materials has begun with the currently available multi-anvil apparatus.

See *Research highlight pp. 43-44*

Published outputs for 2015

CCFS Publications: #578, 656, 668, 675, 685, 706

13 Conference Abstracts

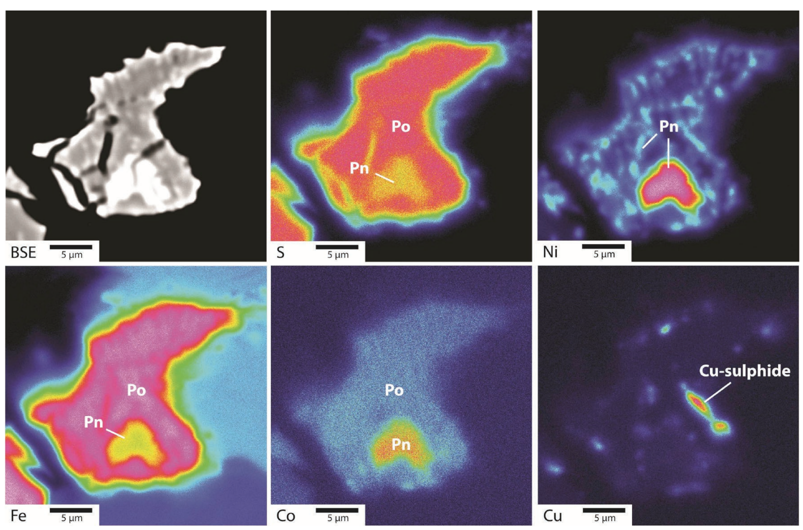
4. ATMOSPHERIC, ENVIRONMENTAL AND BIOLOGICAL EVOLUTION

Theme 1 Early Earth, contributing to understanding Earth's Architecture and Fluid Fluxes.

AIMS

CCFS Flagship Program 4 investigates how the evolution of life and ore deposits were linked to the changing energy state of the whole-Earth System over time, focusing on planetary driving forces that affected all of the different shells of the planet through time, to develop a 4-dimensional conceptual framework of Earth's Evolution. In addition, we apply these Earth-based studies to a better understanding of the evolution of our nearest planetary neighbour, Mars, to guide our understanding of its geological evolution and the search for life within its crust.

Earth's crust represents a complex and dynamically evolving chemical interface between two convective fluid systems: the endosphere (linked core and mantle) and the exosphere (linked hydrosphere and atmosphere). This program investigates how the energy available from the sharp chemical and thermal gradients that exist across this interface changes over time and contributes to the formation of ore deposits, and to the changing nature of atmospheric, environmental, and biological evolution that are linked to the supercontinent cycle.



WDS X-ray elemental distribution map showing a sulfide grain in the olivine-phyric Shergottite Dhofar 019. The sulfide grain is composed of pyrrhotite, with a coarse Co-rich exsolution of pentlandite, as well as a Cu-rich sulfide phase, probably chalcopyrite or cubanite.

2015 Report

FP4 research concentrates on evaluation of the relative importance of (1) the threshold barriers that form in specific environments creating strong chemical and energy gradients in the crust, and the self-organised behaviour of mineral systems and life; (2) the evolving nature of the '*traps*' at the lithosphere-hydrosphere boundary, where life and ore deposits developed through time, as a mechanism to breach these threshold barriers (and to be preserved); (3) the global scale cycle of key chemical elements and heat transfer deemed essential for the evolution of life and formation of ore deposits; and (4) the 4-D evolution of the planetary system and the associated pathways that connect different geochemical reservoirs through time, linked to the changing tectonic style of the planet.

Research activity in CCFS Flagship Program 4 involves primarily cross-node cooperation between UNSW and UWA associated with many external collaborators and concentrates on early Earth processes. Several sub-projects are currently under way:

(1) Geochemical and stable isotopic compositions of carbonate minerals in Pilbara greenstones from well constrained environmental conditions as a guide to early Earth fluid compositions

(2) 3.7 Ga stromatolites from Isua, Greenland, as a new benchmark for the oldest evidence of life on Earth

(3) A study of hotsprings and geysers in the stromatolitic 3.48 Ga Dresser Formation (Pilbara), which are providing new evidence of early life having thrived in hotpsrings on land

(4) The role of microbes in the precipitation of '*buckshot*' pyrite and gold in the 2.76 Ga Hardey Formation, Fortescue Group, Pilbara

(5) Adaptation of the biosphere to the rise of atmospheric oxygen, using a well preserved unit from the 2.4 Ga Turee Creek Group in Western Australia

(6) A study to quantify possible sources of contamination in organic geochemical studies of Archean and Proterozoic rocks

(7) The role of the supercontinent cycle in changing rates of energy transfer between mantle/crust and atmosphere/hydrosphere/biosphere

(8) The implications Archean hotspring results have for the search for life on Mars

(9) The potential of Martian magmatism for Ni-Cu-PGE sulfide mineralisation similar to those associated with the suites of mantle plume-related, mafic to ultramafic komatiites and ferropicrites on Early Earth

See *Research highlights pp. 36-37, 50-51, 52-53, 66-67*

Published outputs for 2015

CCFS Publications: #380a, 492, 498, 499, 500, 632, 636, 712, 759, 766, 768, 785

10 Conference Abstracts

5. DETECTING EARTH'S RHYTHMS: AUSTRALIA'S PROTEROZOIC RECORD IN A GLOBAL CONTEXT

Themes 2 and 3, Earth's Evolution and Earth Today, contributing to understanding Earth's Architecture.

AIMS

Earth's history is considered to have been dominated by cycles of supercontinent formation and breakup. This program tests this hypothesis and its relevance to Australia's geological evolution and assesses its positions during the supercontinent cycles by examining the palaeomagnetic, petrological and detrital provenance record of the Australian continent. By comparing Australian rocks with global analogues, we aim to extend our knowledge about supercontinent cycles and the evolution of the Australian continent to the Palaeoproterozoic and further back in time. Such knowledge is fundamental for understanding the first-order fluid cycles that controlled the formation and redistribution of Earth resources, and the establishment of a 4D global geodynamic model.

We are examining the position of the Australian continent during supercontinent cycles and its record of plume events through a multidisciplinary study of Australian rocks. We focus on the following scientific questions: (1) Was Australia neighboured by East Asian continental blocks during the assembly of Gondwanaland? If yes, which ones, and what was their collision and breakup history? (2) Was there indeed a 40° rotation between northern and southern Australia during the Neoproterozoic that led to the formation of the Paterson-Peterman intraplate orogen? (3) When and how was the Australian Precambrian basement joined together? (4) What was Australia's role in the configuration and evolution of Pre-Rodinia supercontinent(s)?

2015 Report

New palaeomagnetic data from the ~2.4 Ga Erayinia dykes in eastern Yilgarn craton led to a new reconstruction of the Palaeoproterozoic Superia Supercraton (*Pisarevsky et al, 2015*). We also published a global synthesis of the timing and locations of collisional and accretionary orogens, and average plate velocities as deduced from palaeomagnetic and palaeogeographic data over last 2.5 Ga (*Condie et al, 2015*). New reconstructions of São Francisco-Congo, North China and Siberia's positions in Nuna using LIP record, plus geochronology and palaeomagnetic data (*Cederberg et al., 2016*) and first palaeomagnetic data from New Siberian Islands (Russia) and a reconstruction of Palaeozoic Arctida continent (*Metelkin et al., 2016*) have also been completed. Pisarevsky co-edited a Precambrian Research special issue (*v. 259, 2015*) on supercontinental cycles and geodynamics, and Li and collaborators edited a CCFS-sponsored *Geological Society of London Special Publication 424* on Supercontinent Cycles Through Earth History (http://sp.lyellcollection.org/online-first/424), which will be published in 2016.

We conducted a first sampling trip to the Yilgarn Craton. Samples from >20 new dykes, together with samples from >10 dykes previously sampled by ZX Li, are being analysed for palaeomagnetism (PhD student Yebo Liu), and geochemistry and geochronology (PhD student Camilla Stark and Hons student Sarah Champlain). Preliminary results suggest the presence of multiple Proterozoic dyke swarms in the region, and at least some of them still retain their primary magnetic remanence. More sampling is planned in 2016, and analytical work continues.

Dyke samples from Bunger Hills and Vestfold Hills of East Antarctica, obtained through national and international collaborations, are also being investigated for their ages, and geochemical and palaeomagnetic signatures.

Yao conducted a field trip to examine the Ediacaran-Silurian paleogeography of the western Yangtze margin in collaboration with China Geological Survey. Provenance analysis of the Lower Palaeozoic Nanhua Basin have been published (Yao et al., 2015). Work on Hainan Island and northwestern Australia are progressing well.

See *Research highlight p. 61*

Published outputs for 2015

CCFS Publications: #461, 468, 469, 517, 520, 584, 590, 604, 642, 648, 687, 723, 750, 789, 790

15 Conference Abstracts

6. FLUID REGIMES AND THE COMPOSITION OF THE EARLY EARTH

Themes 1 and 3, Early Earth and Earth Today, contributing to understanding Earth's Architecture and Fluid Fluxes.

AIMS

Zircon crystals are currently the only material that records events in the first 500 million years of Earth's history, since no rocks have survived from this period and no other minerals have been established as Hadean in age. There is growing evidence from the study of these zircon crystals that the Earth stabilised rapidly after accretion and that both solid rock and liquid water were present within 150 million years of its formation. In this program, the geochemical signatures of zircon crystals from all known Hadean and early Archean localities will be utilised, together with geochemistry of the oldest known rocks and the application of geophysical and geochemical modelling, to establish how the first crust evolved, why it was destroyed and the role of fluids in this process. It will also evaluate the changes that took place throughout the Archean as crustal processes evolved. In addition, work will continue on Martian meteorites and lunar samples in order to provide further constraints on the early history of the Solar System, especially the role played by fluids.

Sergei Pisarevsky, Camilla Stark and Yebo Liu sampling dykes in the Yilgarn.

2015 Report

Work continued on zircons obtained from Labrador and the North China Craton (NCC). Preliminary results from Labrador indicate a possible extension of the ancient gneisses. A Nd study was initiated on TTG rocks from the NCC with ages between 3.8-3.0 Ga to test for systematic variations with age. Zircon U-Pb and Lu-Hf analyses were undertaken on samples from Aker Peaks in Kemp Land, Antarctica. The presence of nanospheres of metallic lead in Napier Complex zircons was published in the Proceedings of the National Academy of Sciences of the United States. This has important implications for the veracity of U-Pb ages of zircon, especially in rocks that have undergone more than one episode of high-grade metamorphism.

Work continued on the Tarim Craton in association with Nanjing University. Initial indication of 3.5 Ga zircons from the Kuruktag area of northern Tarim has been substantiated, with even older rocks discovered in the vicinity. Work on the Bundelkhand Craton in India continued in association with Prof M. Ram Mohan, with new Lu-Hf data acquired. The granitoid rocks reveal ages very similar to major granitoids developed in the NCC, suggesting a possible linkage in a late Archean supercontinent that also included the Dharwar Craton of India.

The Pb isotopic composition of minerals from Martian meteorites reveal that the least radiogenic Pb measured for each individual sample represents the Pb isotopic composition at the time of crystallisation (initial Pb). These new values define excellent negative linear correlations with $\varepsilon^{143}Nd_i$, $\varepsilon^{176}Hf_i$, and $\varepsilon^{182}W_i$ and a positive linear correlation with $\gamma\,^{187}Os_i$. This suggests differentiation of the Martian mantle affected all radiogenic parent-daughter ratios at a similar time. Lunar work focused on Apollo 14 samples and investigated zircon radiation damage and the age of phosphates. In addition, newly developed techniques have allowed the precise crystallisation ages (2σ errors typically within ± 10 Ma) for several lunar basalts to be determined.

3.7-3.6 Ga trondhjemite veins in biotite schist within the Baijiafen Quarry at Anshan, NE China.

Published outputs for 2015

CCFS Publications: #576, 605, 641, 736, 737, 738, 749, 752, 755, 756, 784

1 Conference Abstract

7. 3D ARCHITECTURE AND PRECAMBRIAN CRUSTAL EVOLUTION IN THE WESTERN YILGARN, AUSTRALIA

Themes 1, 2 and 3, Early Earth, Earth's Evolution and Earth Today, contributing to understanding Earth's Architecture.

AIMS

Iron, Gold and Nickel deposits are of global economic significance, and the Neoarchean Yilgarn Craton and the Proterozoic orogens around its margins constitute one of Earth's greatest mineral treasure troves. Whereas the Yilgarn is one of the best-studied Archean cratons, its enormous size and limited outcrop are detrimental to a deep understanding of what controls the distribution of resources and which geodynamic processes were involved in the tectonic assembly of the Australian continent. The principal aim of this program is to combine geological, geochemical and geophysical techniques to propose a 3D structural model of the lithosphere of the Yilgarn Craton and its margins.

The Yilgarn Craton is a large and highly complex piece of Archean crust with a long history extending from 4.4-2.6 Ga. Amalgamation of terranes is thought to have occurred around 2.65 Ga. Recent work by GSWA in the northwestern part of the craton has identified a long-lived, autochthonous history of crustal development there. There is a growing realisation that understanding how mineralised crustal provinces form requires structural and chemical information on the entire lithosphere. This is addressed in the multi-disciplinary SIEF project "*The Distal Footprints of Giant Ore Systems: UNCOVER Australia*", which involves collaborative research between CSIRO, UWA, Curtin and GSWA, and targets the Capricorn Orogen at the northern boundary of the Yilgarn.

It includes the Capricorn Orogen Passive Array (COPA), a passive source experiment that will study the structure of the deep crust and shallow lithosphere using earthquake seismology. The data from this experiment will be the main source for the local ambient noise inversion, the receiver function common convection point (CCP) stacking techniques, and possibly a body-wave tomography study. Given the fact that the passive source site coverage in Western Australia is sparse and that the available permanent sites in the region provide nearly 10 years of data at isolated locations, several techniques that focus on crust and upper mantle structure beneath single stations will also be applied. This approach has the potential to provide quick access to the crustal and lithospheric structure from these representative sites.

One part of the project aims to generate Lu–Hf isotope data, and integrate them with geological, geochemical, and geophysical information to understand the evolution of continental crust in Western Australia. Efforts are directed at addressing specific geological questions in key areas, particularly along new geophysical transects, as well as in under-explored *'greenfield'* regions, where the new information will improve the targeting

A typical view of a passive seismic station in the COPA experiment; Ashburton Basin, Western Australia.

of mineral exploration and has the potential to provide quick access to the crustal and lithospheric structure from these representative sites.

2015 Report

Huaiyu Yuan produced preliminary maps of the crustal structure in the Capricorn Orogen using seismic receiver functions. The maps show bulk crustal thickness, Vp/Vs ratio, bulk crustal Vp velocity and the crustal density anomaly from gravity inversions. First results show that the crust in the western Capricorn Orogen is thicker, denser and seismic velocities are faster than in the two cratons. The composition of the western Capricorn Orogen is complex, and the results may indicate different terranes or deformation processes during the amalgamation of the Western Australian craton during the Proterozoic. The northern margin of the Yilgarn craton shows anomalous thicker, denser and high speed crust, with an abrupt change in crustal conductivities that are also observed in magnetotelluric studies.

Ruth Murdie and Klaus Gessner, in close collaboration with the

Greg Dering controls the Phantom 2 UAV during photogrammetric imaging of the Moyagee Fault near Cue, Western Australia.

Geological Survey of Western Australia's (GSWA) Editing and Publishing team have produced the first 3D geology digital models that are now available to the exploration industry and the public from the GSWA bookstore. The GSWA's 3D Geomodels include 3D objects as well as the full 2D digital data suite of GSWA's standard digital map packages. The two regions GSWA has modelled, Sandstone and Windimurra, have known deposits of vanadium, and gold, and the models will enhance future exploration potential for more gold, platinum group elements, nickel, and copper.

PhD student Greg Dering is involved in field work in the Yilgarn Craton with Ivan Zibra (GSWA), Joseph White (University of New Brunswick), and Klaus Gessner (GSWA). Greg used his unmanned aerial vehicle (UAV)-based photogrammetric imaging approach to help map the structure of the Moyagee fault, a Neoarchean brittle-ductile shear zone in the Murchison domain, and xenoliths in the Warroan Hill granite outcrop.

Klaus Gessner co-organised an international conference on 3D geological modelling in Margaret River, Western Australia, from 2-7 August 2015: "*Saying goodbye to a 2D Earth*" brought together world leading experts in the field, including key industry representatives.

At the 2015 AGU Fall Meeting in San Francisco Huaiyu Yuan, Klaus Gessner and Vadim Levin (Rutgers University, NJ, USA) convened oral and poster sessions on "*Characterising cratons and craton margins*".

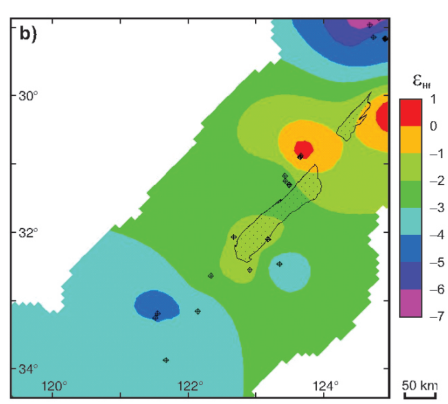
HF isotope mapping of Western Australia

New datasets have been produced from a wide range of regions across Western Australia. A total of 74 zircon samples (>1900 analyses) were selected for Lu-Hf analysis during 2015. The samples were drawn from the Eucla, Musgrave, Rudall, Murchison Domain, and the Amadeus Basin. Over the life of this project 650 zircon samples have been analysed corresponding to 10202 analyses from Tanami, west Arunta, Kimberley, Rudall, Pilbara, Gascoyne, Yilgarn, Musgrave, Albany-Fraser, Officer Basin, Canning Basin, Amadeus Basin, and Eucla.

This project has made excellent progress.

Eucla basement: The age and composition of the Precambrian crystalline basement beneath the Cenozoic Eucla Basin in Western Australia is relatively unknown, yet this is a pivotal region for understanding the Proterozoic construction of Australia. Zircon Hf isotope data were obtained from drillcore samples in the Madura and Forrest regions. These Hf datasets lack significant old evolved crust, with magmatism repeatedly driven by at least three sources, including contemporaneous depleted mantle, reworking of preceding MORB-like crust generated at ca. 1950 Ma, and minor evolved material. These isotopic signatures are comparable to those of the Musgrave Province, the northern Gawler margin and parts of the Rudall Province and define an ancient ocean and its subducted and underplated equivalents.

Proterozoic Edmund and Collier Basins, Capricorn Orogen: The 1679-1067 Ma Edmund and Collier Basins, which comprise ~4-10 km of siliciclastic sedimentary rocks, are the youngest depositional element of the Proterozoic Capricorn Orogen - the collision zone between the Archean Pilbara and Yilgarn Cratons. The Edmund Basin has a half-graben structure, but the architecture and tectonic setting of the overlying Collier Basin are still poorly understood. Paleocurrent directions within the Edmund Basin rocks indicate a northerly source for sedimentary detritus, but the age and Lu-Hf isotopic composition of detrital



Contoured surface of εHf from 1800-1600 Ma granites in the Albany-Fraser highlighting the preferential development of the younger mineralised Fraser Zone in a region of enhanced mantle input (samples denoted by crosses).

Members of UWA's CMCA with the new CAMECA NanoSIMS 50L. L-R: Kymette Peck (NRSP), Sean Webb, Heejin Jeon, Ingrid Magtengaard (NRSP), Haibo Jiang, Peter King, Paul Guagliardo, Laure Martin, David Sampson, Matt Kilburn.

zircons suggest they were derived ultimately from the Gascoyne Province basement to the south. This helps to refine our understanding of basin evolution.

All data are available through GeoVIEW.WA (http://www.dmp.wa.gov.au/geochron/), an online GIS-based mapping tool that allows users to view, query, and map various geology, resources and related datasets.

See *Research highlights pp. 34-36, 41-42, 64-65*

Published outputs for 2015

CCFS Publications: 380a, 441, 497, 497a, 518, 524a, 574, 594, 594a, 629, 637, 649, 710, 717, 722, 724, 726, 730, 735, 740, 742, 743, 761, 769, 776, 782

11 Conference Abstracts

WHOLE OF CENTRE TECHNOLOGY DEVELOPMENT

1. CAMECA ION MICROPROBE DEVELOPMENT: MAXIMISING QUALITY AND EFFICIENCY OF CCFS ACTIVITIES WITHIN THE UWA ION PROBE FACILITY

Themes 1, 2 and 3, Early Earth, Earth's Evolution and Earth Today, contributing to understanding Earth's Architecture and Fluid Fluxes.

AIMS

The Ion Probe Facility within the CMCA at UWA is one of the best-equipped Secondary Ion Mass Spectrometry (SIMS) labs in the world. It houses a CAMECA IMS 1280 large-radius ion microprobe, for the high-precision analysis of stable isotopes in minerals, and two CAMECA NanoSIMS 50s for imaging mass spectrometry at the sub-micron scale. This program provides a dedicated Research Associate to facilitate CCFS activities and lead the development of standards and analytical protocols at the CMCA. This will greatly benefit the CCFS by increasing the capacity of the Facility, enabling a higher degree of interaction and participation on research projects, facilitating standards and protocols development, and allowing greater synergy with other CCFS node facilities.

2015 Report

The Ion Probe Facility enjoyed a very good year in 2015, with the addition of a new NanoSIMS 50L, and several new members to the SIMS team (Heejin Jeon, Paul Guagliardo and Haibo Jiang). It was also a productive year for the IMS1280, which clocked up almost 4000 hours and contributed to more than 20 projects.

One of the most time intensive projects was the continued development of quadruple S isotope analyses (^{32}S, ^{33}S, ^{34}S and ^{36}S) in sulfide minerals. This project, initiated by John Cliff, who left the lab in 2014, and continued by Crystal LaFlamme, Laure Martin, Heejin Jeon and Matt Kilburn, has now produced a continuous data set that spans several years. A manuscript featuring the development of in-house standards for pyrite, chalcopyrite, arsenopyrite, pyrrhotite and pentlandite, is currently under review.

These protocols have been applied to a number of projects, as an exploration tool, and for Archean-Proterozoic orogens, such as the Capricorn Orogen, Western Australia (Crystal LaFlamme, Vikraman Selvaraja), and the Ammassalik Intrusive Complex, Greenland (Anne Johannesen).

High-precision O isotope analyses continue to be a staple for the lab, and were applied to U/Pb-dated zircons from igneous rocks in the Rudall Province of Western Australia (Chris Kirkland), Tibet/Himalaya (Yongjun Lu), Superior Province, Canada (Katarina Bjorkman), and granites of the Tanami Orogen, Northern Territory, Australia (Linda Iaccheri).

As part of the CCFS pilot project "*Fluid fluxes and architecture in subduction zones: insight from O and H isotopes in Lawsonite*", two potential reference materials have been identified as homogeneous and will be further characterised for H isotope analyses. The other CMCA-based pilot project "*How to make the invisible visible...*" produced some spectacular results from the NanoSIMS 50. Mineral-fluid experiments carried out at Macquarie University using ^{18}O-labelled water were imaged with the NanoSIMS, revealing how atoms move between phases at the mineral-melt interface. This work was carried out by MQ PhD student Liene Spruzeniece and UWA Honours students Jack Adams and Haydn White.

Published outputs for 2015

CCFS Publications: #380a, 489, 519, 527, 557, 601, 742, 751, 771

5 Conference Abstracts

2. FRONTIERS IN INTEGRATED LASER-SAMPLED TRACE ELEMENT AND ISOTOPIC GEOANALYSIS

Themes 1, 2 and 3, Early Earth, Earth's Evolution and Earth Today, contributing to understanding Earth's Architecture and Fluid Fluxes.

AIMS

The overall aim is to develop new analytical methods for *in situ* measurement of trace elements and isotope ratios to support and enable CCFS research programs and to provide new directions of research. Specific objectives include:

(1) combined trace element and isotope analysis – '*split-stream*' analysis

(2) development of '*non-traditional*' stable isotopes

(3) characterisation of reference materials for elemental and isotope ratio measurement

(4) development of data reduction software for combined trace element and isotope analysis

2015 Report

Dr Yoann Gréau (see *p. 13*) was appointed as a Research Associate in July 2015 to assist in the development of split-stream methods using femtosecond laser, Q-ICP-MS and Nu Plasma II.

Instrument progress 2015: Planned innovations were based on new instruments funded by ARC LIEF grants in 2010 (Q-ICP-MS, SF-ICP-MS and femtosecond laser) and 2012 (MC-ICP-MS). This new infrastructure provides the capability to develop '*split-system*' techniques in which two mass spectrometers (a MC-ICP-MS and an ICPMS) are connected to a common laser source for novel simultaneous measurement of geochemical parameters.

Progress in 2015 included:

Nu Plasma II MC-ICP-MS was installed in June 2015 following the decommissioning of Nu Plasma 005 after 16 years of service. The second generation Nu Plasma has an expanded collector array (16 Faraday cups and 5 ion counters) and enhanced sensitivity compared to the older instruments, which have already led to improvements in a variety of *in situ* techniques (e.g. U-Pb in zircon, Re-Os in sulfides) and stable metal isotopes (e.g. Mg).

Upgrade to Nu Plasma HR 034: A new enhanced interface was installed as part of an upgrade of this 11 year-old instrument in June 2015. The upgrade has increased sensitivity between 1.5 and 2 times, and this has contributed to an overall improvement in the precision of single measurements and long-term reproducibility.

Photon Machines Excite 193nm laser system: In 2015 a third excimer laser microprobe was installed and co-located with one of the Nu Plasma MC-ICP-MS to establish the laser ablation split-stream infrastructure.

Split-stream analysis: The development of the split-stream methods was postponed until the Nu Plasma II was installed due to performance issues with Nu Plasma 005. Preliminary experiments indicate that sensitivity will be a critical issue for the viable simultaneous analysis of U-Pb and Hf isotopes in zircon.

Development of new sample preparation methods for geochemical and isotope analysis: New methods developed for the analysis of radiogenic isotopes (Rb-Sr, Sm-Nd and Lu-Hf) at ultra-low levels and/or small sample volumes were applied to mantle peridotites and pyroxenites (Nicole McGowan PhD, Romain Tilhac PhD, Jianggu Lu PhD). The development of Mg isotope methodologies for chromite and chromite-rich ultramafic rocks as part of the TARDIS Program (Nicole McGowan PhD) was completed; high-precision results were obtained in wet-plasma mode on the Nu Plasma II and corroborated by replicate measurements at IGGCAS, Beijing.

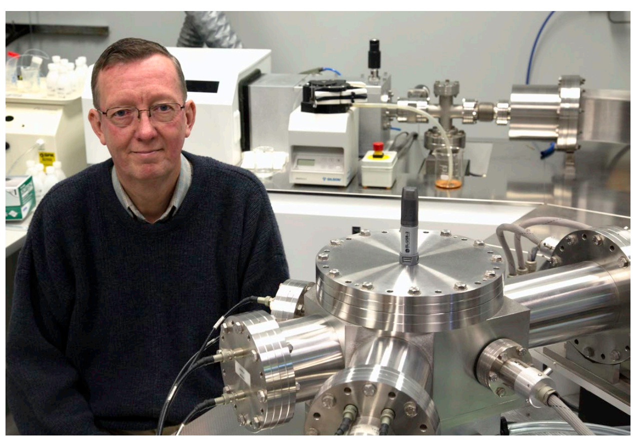
Evaluation of standard reference materials (silicate) for combined measurement using laser ablation ICP-MS and MC-ICP-MS: The development of potential microbeam standards for combined laser ablation ICP-MS and MC-ICP-MS requires characterisation of the chemical (major and trace elements) and isotopic compositions. Approaches taken are:

- investigation of U-Pb geochronology of zircon by femtosecond laser ablation
- investigation of ablation processes of sulfides using Excimer and femtosecond laser systems
- assessment of a variety of common-Pb bearing accessory minerals (e.g. apatite, rutile, titanite) for U-Pb geochronology
- on-going development of garnet standards for *in situ* measurement of Mg isotopes (laser ablation MC-ICPMS and SIMS; in collaboration with Profs Jin-hui Yang and Fu-Yuan Wu at IGGCAS, Beijing) and O isotope composition (SIMS development in collaboration with UWA-CMCA)

Incorporation of operating protocols for combined laser ablation ICP-MS and MC-ICP-MS data into GLITTER data reduction software: Revision of GLITTER continued in 2015 to enable the simultaneous treatment of combined trace-element and isotope ratio measurements. Glitter support for output from the Nu Plasma II has been implemented and plans to add radiogenic isotope systems such as Lu-Hf, Re-Os, Nd-Sm and Rb-Sr have commenced.

Published outputs for 2015

2 Conference Abstracts



Norman Pearson with the Nu Plasma II MC-ICP-MS, installed in June 2015.

Appendix 2: CCFS workplan 2016

1. TARDIS II: DEEP-EARTH FLUIDS IN SUBDUCTION ZONES, OPHIOLITES AND CRATONIC ROOTS

- Fieldwork and geochemical studies of Tibetan ophiolites will continue, working toward an overall model for the development of the Tethyan oceanic lithosphere and its evolution
- Initiation of a major research project on the evolution of the Tethys belt in Iran, involving field work, studies of ophiolites and chromitites, isotopic mapping of hidden crust, geochemical studies of young magmatic rocks, and integration with deep-seismic traverses being carried out by IGG-CAS (Beijing)
- The Cabo Ortegal project will be continued, turning the focus toward structural aspects
- Continuation of xenolith work on Asian localities and on Sc in laterites (industry collaboration project)
- Completion of the work on the Pannonian Basin
- Further detailed work on the Israeli volcanic ejecta, including microchemical, isotopic and crystallographic studies of the dozens of unidentified phases (industry collaboration project)

2. MULTI-SCALE FOUR-DIMENSIONAL GENESIS, TRANSFER AND FOCUS OF FLUIDS AND METALS

In 2016, the planned work for the three modules of Fertility, Architecture and Transient Geodynamics will advance as follows:

Fertility

- More experiments with sulfur at varying fO_2, with volatiles such as Cl, CO_2, and Br, will be run to establish the role of volatiles in the metal transport capacity of melts
- Master study of Bataa Bataar and postdoctoral appointment of Luis Parra-Avila to build knowledge capacity to develop reliable heavy mineral indicators in the exploration for magmatic-hydrothermal mineral systems
- Honours project of Alison David and ongoing PhD project of Greg Dering to unravel the mechanisms and dynamics of mafic intrusion emplacement relevant to the formation of magmatic sulfide deposits
- Ongoing PhD study of Greg Poole aiming to put forward a new metallogenic model for porphyry-related and epithermal systems of the Permian-Triassic Choiyoi Group in the Cordillera Frontal, Argentina
- Ongoing PhD study of Jason Bennett aiming to develop cassiterite (SnO_2) as the zircon ($ZrSiO_4$) *'equivalent'* for tin bearing mineralised systems
- Postdoctoral appointment of Erwann Lebrun to generate radiogenic and stable isotope constraints of the genesis of Ni-Cu-PGE mineralisation in the Johan Petersen Intrusion, Ammassalik Intrusive Complex, Tasiilaq area, SE Greenland
- Postdoctoral appointment of Johannes Hammerli involving the application of the new ARC-funded split stream LA-(MC)-ICP-MS facility at UWA to unlock the potential of detrital minerals in exploration targeting

Architecture

- PhD study of Eunjoo Choi to unravel the architecture of the Archean lithospheric mantle of the Yilgarn Craton through careful understanding of alkaline magmatism in space and time
- Wrapping up of the PhD studies on the four dimensional lithospheric evolution and controls on mineral system distribution in Neoarchean to Paleoproterozoic terranes in North America, West Africa and North Australia
- Master study of Jack Stirling on the geochronology of the Lower Crustal Cumulate Complexes in the Kohistan Terrane, Northern Pakistan

Transient Geodynamics

- Postdoctoral appointment of Chris Gonzalez on *"Petrological-thermomechanical modeling of the behaviour of CO_2 in the mantle–lithosphere"*
- Ongoing CET-CCFS-wide effort to better constrain ore forming processes that occur at craton margins
- Postdoctoral appointment of Weronika Gorczyk to establish magma emplacement in 3D

3. TWO-PHASE REACTIVE FLOW IN MULTI-COMPONENT DEFORMABLE MEDIA

With the maturity of the modelling techniques now demonstrated, 2016 will largely see their progressive application to problems relevant to the aims of this project. This will involve a suite of simulations exploring the dynamics of subduction over Earth's history, and its effect on fluid systems. We will also be further integrating the newly developed advanced methods for multiphase/component flow, with large-scale geodynamic flow models, to explore the effects of realistic fluid release and migration on geodynamic model predictions, and integrating these with seismology constraints.

Seismology components of this project will focus on imaging the lithosphere-asthenosphere system in NE China, where the oceanic subduction in the east has profound impacts on geologic features, such as, the destruction of NE China Craton keels, extensive intraplate volcanism and a systematic variation of topography from west to east.

The experimental laboratory build-up will be continued, with acquisition of additional high-pressure equipment including laser-heated diamond-anvil cells to complete the pressure range relevant for '*core to crust*' applications from next year.

4. A PLANETARY DRIVER OF ATMOSPHERIC, ENVIRONMENTAL AND BIOLOGICAL EVOLUTION THROUGH TIME

CCFS Flagship Program 4 will focus on the following projects in 2016:

- Origin of life in terrestrial hotsprings. Following on from discoveries of hotspring deposits in the 3.48 Ga Dresser Formation of the Pilbara Craton, Australia, this collaborative research will focus on the availability of elements and complexity in terrestrial hotsprings as a setting for the origin of life
- Composition of Early Archean hydrosphere and atmosphere, using carbonate mineralogy and stable isotope geochemistry to constrain seawater and hydrothermal fluid compositions, from the Pilbara Craton of Western Australia
- The role and geometry of hydrothermal fracture networks in transporting heat and minerals in fluids to the surface and how these interact with ancient life
- Microbial role in the precipitation of '*buckshot*' pyrite and gold in the 2.76 Ga Hardey Formation, Fortescue Group, Pilbara Craton
- Adaptation of the biosphere to the rise of atmospheric oxygen, as preserved in a 2.4 Ga stromatolite-thrombolite carbonate reef succession with black cherts, from Western Australia
- Genesis of orthomagmatic Ni-Cu-PGE sulfide mineralisation on Mars and the role of sulfur in the hydrosphere and implications for the search for life on Mars
- Landing site selection for NASA's Mars 2020 mission - Our work on ancient life on Earth, and the discoveries of hotspring deposits, is being used in the process of site selection for the upcoming Mars mission to search for signs of life
- Whole-Earth tectonics. Integration of planetary, atmospheric and biological evolution, to develop a 4-D framework of causative changes through time

5. DETECTING EARTH'S RHYTHMS: AUSTRALIA'S PROTEROZOIC RECORD IN A GLOBAL CONTEXT

New sampling trips are being planned for Yilgarn dykes, the Gawler Range Volcanics, the Gairdner dyke swarm, and possibly Proterozoic targets in Northern Territory. Palaeomagnetic, geochronological and geochemical investigations on the Yilgarn and Antarctic dykes will continue, and early results will be written up for publication. Samples from the 1.8 Ga Hart Dolerite and Cambrian sandstone of the Kimberly craton, and the Morawa Lavas of the Yilgarn craton, will be analysed in the new palaeomagnetic laboratory at Curtin.

A palaeomagnetic study of 1.9-1.8 Ga and 1.26 Ga mafic intrusions in southern Siberia will be carried out. New palaeomagnetic data from 1.35 Ga mafic dykes in southern Siberia, 1.97 Ga and 1.77 Ga mafic intrusions in Karelia (Russia), will be written up for publication. Systematic interpretation of Ediacaran-Silurian sedimentary settings for the western Yangtze margin will be conducted, and provenance analysis of supplementary Yangtze samples and all Australian samples will be carried out for comparison.

6. FLUID REGIMES AND THE COMPOSITION OF THE EARLY EARTH

The Nd study of the Anshan gneisses in the NCC will be completed in 2016 and the results prepared for publication. Further work on Antarctic zircons will involve the use of NanoSIMS and the Atom Probe at Curtin to further clarify the nature and distribution of the Pb nanospheres and the mobility of other elements affected by the high-grade metamorphism. The newly-identified >3.5 Ga rocks in the northern Tarim Craton will be resampled in March 2016 and zircons analysed on the Curtin SHRIMP later in the year. Dr Ge of Nanjing University will join Curtin staff in mid-2016 and commence a re-investigation of the ancient zircons from the Jack Hills site. This will involve getting back to basics and utilising a strict set of criteria in order to identify the most pristine Hadean grains. This will result in identifying the basic geochemical and isotopic parameters that define the World's oldest fragments, which are currently 'hidden' by a wealth of data that were not necessarily collected in the most rigorous and appropriate manner.

Work on modelling the early Earth, flagged in 2015, will commence with CI O'Neill and Prof Calo at Curtin. Work on extra-terrestrial samples will continue in association with the Swedish Museum in Stockholm. This will include both Martian meteorites and Apollo 14 Lunar samples.

7. 3D ARCHITECTURE AND PRECAMBRIAN CRUSTAL EVOLUTION IN THE WESTERN YILGARN, AUSTRALIA

Klaus Gessner and Ruth Murdie will focus on regional 3D modelling studies, potential field interpretations accompanying the seismic interpretation of the Eucla–Gawler seismic survey, and on field support for projects in Murchison Domain, Capricorn Orogen and Albany-Fraser Orogen.

3D models and accompanying GSWA Records are planned for the Albany–Fraser Orogen, and work will continue on a 3D fault network model for the northwest and central Yilgarn Craton. Huaiyu Yuan will investigate crustal structure of the Capricorn Orogen and the architecture of the lithospheric mantle in increasing detail. A suite of passive source methods will be applied in conjunction with the COPA to develop a technical template for resolving seismic anisotropy structure for long-operating stations.

HF isotope mapping of Western Australia
The continued acquisition of Hf isotopic datasets on previously dated (U-Pb SHRIMP)) zircon samples from Western Australia will proceed, in concert with interpretation and integration with other chemical and remotely sensed information to enhance the precompetitive understanding of geoscience across Western Australia. The project will aim to increase the Hf isotopic database for the state by at least 100 samples in 2016.

WHOLE OF CENTRE TECHNOLOGY DEVELOPMENT

1. CAMECA ION MICROPROBE DEVELOPMENT: MAXIMISING QUALITY AND EFFICIENCY OF CCFS ACTIVITIES WITHIN THE UWA ION PROBE FACILITY

Work will commence or be continued in the following areas:

- Development of analytical protocols for oxygen and carbon isotopes in carbonates
- Improvement of analytical protocols for S isotopes will be continued, to solve matrix effects in sulfides with complex chemistry
- Pilot projects will be continued, looking at the development of hydrogen isotope analyses in Lawsonite and isotopic labelling analysis of mineral exchanging with fluids
- The analysis of isotopes from the new NanoSIMS 50L will be developed

2. FRONTIERS IN INTEGRATED LASER-SAMPLED TRACE ELEMENT AND ISOTOPIC GEOANALYSIS

Work will commence or be continued in the following areas:

- Development of standard operating procedures for *in situ* U-Pb isotope measurements on the Nu Plasma II
- Refinement of standard operating procedures for *in situ* Re-Os isotope measurements on the Nu Plasma II
- Finalisation of the first phase of an experimental program to investigate fundamental properties of femtosecond ablation processes in geological materials (zircon)
- Continuation of the second phase of investigation of ablation processes of non-silicates – fluorite, sulfides, oxides, phosphates, and carbonates
- Commence development of split-stream laser ablation analysis using Q-ICP-MS (U-Pb isotopes) and MC-ICP-MS (Hf isotopes)
- Development of *in situ* Mg-isotope measurement of olivine by femtosecond laser ablation
- Development of methods for the measurement of Fe isotopes in chromite and chrome-rich ultramafic rocks
- Continuation of transfer of *in situ* methodologies for trace-element analysis from Q-ICP-MS to Nu Attom
- Continued development of Glitter software, focusing on incorporation of radiogenic isotope systems for Nu Plasma II

Appendix 3: Independently funded basic research projects

Independently funded research projects within CCFS contribute to the long-term, large-scale strategic goals and play an important role in determining the shorter-term research plans. Research goals for each year are thus linked to the aims of funded projects. Summaries of the current independently funded CCFS-related projects are given below. For Industry funded projects see *Industry Interaction p. 96.*

Down under down under: using multi-scale seismic tomography to image beneath Australia's Great Artesian Basin	N. Rawlinson, **Y. Yang**: *Supported by ARC Discovery (commenced 2011)* ***Summary:*** Seismic arrays will be deployed in the Great Artesian Basin to image the crust and mantle using distant earthquake and ambient noise sources. This will answer fundamental questions about the tectonic evolution of eastern Australia and elucidate the structure of a region containing significant deep Earth resources.
Unravelling the geodynamics of eastern Australia during the Permian: the link between plate boundary bending and basin formation	G. Rosenbaum, **S.A. Pisarevsky**, C.R. Fielding, F. Speranza: *Supported by ARC Discovery (commenced 2013)* ***Summary:*** The Permian evolution of eastern Australia is poorly understood. It involved bending of the southern New England Orogen and simultaneous development of widespread sedimentary basins. This project will combine palaeomagnetic and structural investigations to unravel the palaeogeography and plate kinematics of eastern Australia during the Permian. We will generate a comprehensive database on palaeolatitudes, block rotations and magnetic fabric, and will link, for the first time, the process of oroclinal bending with the development of the East Australian rift System. Outcomes will elucidate the fundamental tectonic process of oroclinal bending and will fill a knowledge gap in our understanding of the evolution of the Australian continent.
The global consequences of subduction zone congestion	**L. Moresi**, P. Betts, J. Whittaker, M. Miller: *Supported by ARC Discovery (commenced 2015)* ***Summary:*** This project will use a combination of 3D geodynamic modelling, plate kinematic reconstruction and geological and geophysical synthesis to determine how congested subduction zones influence plate kinematics, subduction dynamics and tectonic evolution at orogen and global scales. The project aims to deliver a transformation change in understanding the links between congested subduction, mantle flow, trench migration, crustal growth, transitions between stable convergent margin configurations and deformation in the overriding plates of subduction zones. Determining these relationships is significant because it will provide dynamic context to interpret the geological record of ancient convergent margins, which host a large percentage of Earth's metal resources.
Timescales of mixing and volatile transfer leading to volcanic eruptions	**H. Handley**, **S. Turner**, M. Reagan, J. Barclay: *Supported by ARC Discovery (commenced 2015)* ***Summary:*** The short-lived lead isotope, ^{210}Pb, has the unique ability to place timescale constraints on volcanic processes, such as the input, mixing and degassing of magma. These processes are believed to be of fundamental importance in the triggering of volcanic eruptions. This project will measure ^{210}Pb isotopic compositions and elemental diffusion profiles in crystals of volcanic rocks that represent the end members of mixed magmas to constrain the volume and timescale of volatile transfer from magmatic recharge and also the time between magma mixing events and eruptions. The project aims to test the paradigm that magma recharge triggers volcanic eruptions and aims to yield significant outcomes for understanding eruption triggers at hazardous volcanoes.

Migmatites, charnockites and crustal fluid flux during orogenesis	**I. Fitzsimons**, M. Holness, **C. Clark**: *Supported by ARC Discovery (commenced 2015)* ***Summary:*** Migration of volatile fluid and molten rock controls many Earth processes including rock deformation and the formation of mineral and energy deposits. Deep crustal fluids are hard to study directly, and their characteristics are usually inferred from lower crustal rock brought to the surface by erosion. For over 30 years one such rock called charnockite has been used to argue that lower crust is dehydrated by influx of carbon dioxide-rich fluid, while other evidence supports dehydration by water extraction in silicate melt. This project aims to use the shape, distribution and chemistry of mineral grains to trace the passage of volatiles and melt through charnockite, constrain the nature of lower crustal fluids and resolve a long-standing controversy.
How the Earth works—toward building a new tectonic paradigm	**Z.X. Li**: *Supported by ARC Laureate Fellowships (commenced 2015)* ***Summary:*** This fellowship project aims to build on the latest technological and conceptual advances to establish the patterns of Earth evolution, and use this information to examine a ground-breaking geodynamic hypothesis which links cyclic plate aggregation and dispersion to deep Earth processes. Half a century after the inception of plate tectonics theory, we are still unsure how the Earth '*engine*' works, particularly the forces that drive plate tectonics. The project involves extensive national and international collaboration to potentially create a paradigm shift in our understanding of global tectonics, and hopes to contribute to an understanding of the formation and distribution of Earth resources to provide a conceptual framework for their exploration.
Dating Down Under: Resolving Earth's crust - mantle relationships	**E. Belousova**: *Supported by ARC Future Fellowship and MQ (commenced 2012)* ***Summary:*** How the continental crust has grown is a first-order problem in understanding the nature of the surface on which we live. Was most of the crust formed early in Earth's history or did it grow episodically? Was its growth related to underlying mantle processes? The project will use *in situ* isotopic and trace-element microanalysis of the mineral zircon (a geological '*time capsule*'), extracted from rocks and sediments worldwide, to answer these fundamental questions. It will develop a new model for the timing of crustal formation and the tectonic and genetic links between Earth's crust and mantle. The results will be relevant to the localisation of a wide range of mineral resources.
From Core to Ore: emplacement dynamics of deep-seated nickel sulphide systems	**M. Fiorentini**: *Supported by ARC Future Fellowship (commenced 2012)* ***Summary:*** Unlike most mineral resources, which are generally concentrated in a wide range of crustal reservoirs, nickel and platinum are concentrated either in the core or in the mantle of our planet. In punctuated events throughout Earth history, large cataclysmic magmatic events have had the capacity to transport and concentrate these metals from their deep source to upper crustal levels. This project aims to unravel the complex emplacement mechanism of these magmas and constrain the role that volatiles such as water and carbon dioxide played in the emplacement and metal endowment of these systems.
The timescales of Earth-system processes: extending the frontiers of uranium-series research	**H. Handley**: *Supported by ARC Future Fellowship and MQ (commenced 2012)* ***Summary:*** This project will advance our understanding of the timescales of Earth processes using short-lived (22 to 380,000 years) isotopes. The results will provide better constraints on the timescales of magmatic processes and frequency of large-scale eruptions for volcanic hazard mitigation and also soil production rates for landscape erosion studies.
A new approach to quantitative interpretation of paleoclimate archives	**D. Jacob**: *Supported by ARC Future Fellowship and MQ (commenced 2013)* ***Summary:*** Skeletons of marine organisms can be used to reconstruct past climates and make predictions for the future. The precondition is the knowledge of how climatic and environmental information is incorporated into the biominerals. This project will use cutting-edge nano-analytical methods to further our understanding of how organisms build their skeletons.

Flow characteristics of lower crustal rocks: developing a toolbox to improve geodynamic models	**S. Piazolo**: *Supported by ARC Future Fellowship and MQ (commenced 2012)* ***Summary:*** This project will investigate in detail how rocks flow in the lowest part of the Earth's crust. The results will be used to improve sophisticated computer simulations of large-scale geological processes, allowing a better understanding of earthquakes, the formation of volcanic areas and location of energy resources.
New insights into the origin and evolution of life on Earth	**D. Wacey**: *Supported by ARC Future Fellowship and MQ (commenced 2014)* ***Summary:*** This project aims to provide new insights into the origin of life on Earth, life's diversification through the Precambrian, and the co-evolution of life and early Earth environments. It will be discipline-leading in that it will take the study of early life to the sub-micrometre and hence sub-cellular level. This will facilitate new opportunities for identifying the types of life present during early Earth history, their metabolisms, cellular chemistry and interactions with their environment. This project aims to also provide new search engines and more robust assessment criteria for life on other planets, and help to resolve specific scientific controversies, for example, the validity of claims for cellular life from 3.5 billion-year-old rocks.
Roles of deep-Earth fluid cycling in the generation of intra-continental magmatism	**X.C. Wang**: *Supported by ARC Future Fellowship and MQ (commenced 2014)* ***Summary:*** This project aims to test a provocative and potentially ground-breaking hypothesis that fluid released from subducted oceanic slabs and stored in the mantle transition zone, may trigger or control some major intra-plate geotectonic phenomena. It aims to provide a self-consistent model that links geological processes occurring at plate boundaries with those far-field effects well away from plate boundaries via deep-Earth fluid cycling. The outcomes of this project aim to help to better understand links between plume and plate tectonic processes in the first-order dynamic system of Earth, and identify ways to improve success in future mineral exploration.
How the Earth moves: Developing a novel seismological approach to map the small-scale dynamics of the upper mantle	**Y. Yang**: *Supported by ARC Future Fellowship (commenced 2013)* ***Summary:*** The concept of small-scale convection currents from about 100-400 km below the Earth's surface is a model proposed to explain the origins of intraplate volcanoes and mountains. However, direct evidence for the physical reality of small-scale convection cells is generally weak. This project will develop a novel seismological approach combining both ambient noise and earthquake data that can image such small-scale upper mantle convection. The outcomes of this project will help to fill the gap left in the Plate Tectonic paradigm by its inability to explain intraplate geological activity (volcanoes, earthquakes, mountains), which would be a significant step towards unifying conceptual models about how the Earth works.
Earth's origin and evolution: a sulphurous approach	**O. Alard**: *Supported by ARC Future Fellowship (commenced 2015)* ***Summary:*** This project aims to shed new light on global element cycles in the deep Earth and how they connect to the evolution of the exospheres – one of the hottest topics in geosciences. It also aims to produce key knowledge of the extraction and transport of elements from the deep Earth to the surface, which may provide valuable information for resource exploration. Using novel integrated elemental and isotopic approaches, this program aims to track the origin and fate of sulfur, selenium and tellurium during accretion and subsequent redistribution in fluids to Earth's surface. This new knowledge is critical to understanding how these and other elements of strategic and economic importance, such as the Platinum Group Elements, are extracted from the deep Earth and transported to the surface.

Measuring mantle hydrogen to map ore fluids and model plate tectonics	**K. Selway**: *Supported by ARC Future Fellowship (commenced 2015)* ***Summary:*** The goal of this project is to use magnetotellurics to measure mantle hydrogen content to aid in the discovery of new mineral deposits. Hydrogen controls the strength of Earth's mantle and is a vital component of the systems that form giant ore deposits. However, mantle hydrogen content is unconstrained. Ore-forming fluids hydrate the mantle pathways on which they travel. The first aim of this project is to image these fluid pathways to improve mineral exploration techniques. Plate tectonic models assume that the lithospheric mantle is dehydrated but existing data from magnetotellurics and mantle rocks show high hydrogen contents. The second aim of this project is to create a map of the hydrogen content of the plates, which may lead to new models for continental evolution and mantle dynamics).
A new approach to revealing melting processes in the hidden deep Earth	**A. Giuliani**: *Supported by ARC DECRA (commencing 2015)* ***Summary:*** Kimberlite magmas are very rich in volatiles (for example carbon dioxide and water); they are the major host of diamonds and provide the deepest samples from Earth's mantle. The primary compositions of these melts can provide unique information on the nature of the deep mantle. However, kimberlite melts mix and react with wall rocks on the way up, obscuring their primary composition. To see through these secondary processes, the project aims to use a novel approach integrating the study of melt inclusions in magmatic minerals with analysis of radiogenic and stable isotopes, and investigating reactions between kimberlite magmas and wall-rock fragments. The project aims to provide new understanding of the constraints on melting processes and recycling of crustal material in the deep mantle.
Australian membership of the International Ocean Discovery Program	R.J. Arculus, E.J. Rohling, A.P. Roberts, N.F. Exon, C.J. Yeats, **S.Y. O'Reilly**, **S.C. George**, D. Muller, J.C. Aitchison, J.M. Webster, M.F. Coffin, P.M. Vasconcelos, K.J. Welsh, **T.C. McCuaig**, A.D. George, C.G. Skilbeck, A.T. Baxter, J.M. Hergt, S.J. Gallagher, C.L. Fergusson, C.R. Sloss, A.D. Heap, W.P. Schellart, J.D. Stilwell, J.D. Foden, A.P. Kershaw, W.R. Howard, M.B. Clennell, J.J. Daniell, L.B. Collins: *Supported by ARC LIEF (commenced 2014)* ***Summary:*** This project is for an Australian membership of the International Ocean Discovery Program. The Program will recover drill cores, situate observatories, and conduct down-hole experiments in all the world's oceans from lowest to highest latitudes to address fundamental questions about Earth's history and processes within four high-priority scientific themes: climate and ocean change - reading the past and informing the future; biosphere frontiers - deep life, biodiversity, and environmental forcing of ecosystems; earth connections - deep processes and their impact on earth's surface environment; earth in motion - processes and hazards on a human time scale.
Expanding the frontiers of mass spectrometry: a high resolution laser ablation multiple streaming facility	A. Kemp, M. McCulloch, **M. Fiorentini**, **T. McCuaig**, A. Rate, **C. Clark**, B. Rasmussen, N. Evans, **S. Reddy**, P. Bland, T. Raimondo, **N. Pearson**, **E. Belousova**, **D. Jacob**, D. Rubatto, C. Spandler, S. Barnes: *Supported by ARC LIEF (commenced 2015)* ***Summary:*** This geochemical facility with an innovative, world-leading micro-analytical capability intends to support research of fundamental and strategic problems at the frontiers of the Earth and Environmental Sciences. The facility aims to allow new insight into the age, composition, thermal history and structure of the Australian continent, as necessary for delineating mineral endowment and for tracing the sources of ore metals. It will provide a higher resolution record of climate and environmental change which will better inform assessment of the impacts, both locally and regionally. It is intended that the facility will amplify national and international scientific collaboration and create unique research opportunities for Australian-based scientists.

A fully automated, fully shielded palaeomagnetic system	**Z.X. Li,** E. Tohver, A. Roberts, G. Rosenbaum, **C. O'Neill**, **S. Pisarevsky**, **C. Clark**, C. Elders, P. Bland, **S. Wilde**: *Supported by ARC LIEF (commenced 2015)* ***Summary:*** This project aims to establish the first fully automated and magnetically fully shielded superconducting palaeomagnetic data acquisition system in Australia. Palaeomagnetism is a key research field that has applications to a broad range of pure and applied geoscience disciplines. Australia has been a world leader in this field, including the application of palaeomagnetism to both global and regional tectonic studies. Palaeomagnetic studies demand a labour-intensive process of treating and measuring a large number of samples. The system will significantly enhance the efficiency and accuracy of palaeomagnetic analysis, and thus enhance Australia's research capacity in this and related research fields.
Mineral Systems Flagship Cluster	**T.C. McCuaig*:*** *Supported by CSIRO Flagship Collaboration Fund (commenced 2013)* ***Summary:*** As Australian mineral exploration moves into areas of deep cover, the expense of exploration drilling will increase dramatically. Explorers will demand increasingly sophisticated targeting tools to plan drilling programs and an improved understanding of the processes that influence the transport and deposition of metals by ore-forming fluids. The cluster has 3 Themes to deliver on each of the advertised requirements notably: Theme 1: An experimental program to assess the behaviour of meta-stable organic compounds in targeting mineral systems and validate thermodynamic models and interpretations. Theme 2: A complementary field program aimed at providing data from key mineral systems to support the thermodynamic and experimental programs. Theme 3: An integrated thermodynamic treatment of organic and inorganic systems that includes recently documented organometallic complexes.

Appendix 4: Participants list

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Ms Sally-Ann Hodgekiss, Reporting & Coms. Manager (MQ)
Ms Summer Luo, Centre Finance & Admin Officer (MQ)
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Dr Mike Etheridge	Professor Alan Jones	Dr John Vann
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Dr Richard Glen	Dr David Leach	Dr Peter Williams
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Dr Graham Begg	Dr Bram Janse	Dr Thomas Statchel
Dr Christoph Beier	Dr Felix Kaminsky	Mr Huayun Tang
Dr Phillip L. Blevin	Dr Hans-Rudolf Kuhn	Ms Nancy van Wagoner
Professor Hannes Brueckner	Ms Qian Liu	Dr Kuo-Lung Wang
Mr Robert Bultitude	Mr Qingyong Luo	Professor Xiang Wang
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Mr David Child (MQ)	Mr Erwann Lebrun (UWA)	Mr David Stevenson (UWA)
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Mr Stephen Craven (MQ)	Mr Shaojie Li (CU)	Mr Rajat Taneja (MQ)
Miss Daria Czaplinska (MQ)	Miss Nora Liptai (MQ)	Ms Ni Tao (CU)
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Mr Denis Fougourouse (UWA)	Mr Quentin Masurel (UWA)	Mr James Warren (UWA)
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Ms Tara Djokic (UNSW)	Ms Colleen McMahon (MQ)	Mr Jonathon Poh (MQ)
Ms Victoria Elliott (MQ)	Ms Uvana Meek (MQ)	Ms Valerie Roy (MQ)
Mr Jean-Antoine Gazi (MQ)	Ms Lauren Miller (MQ)	Mr Sahand Tadbiri (MQ)
Mr Mitchell Gerdes (MQ)	Ms Josephine Moore (MQ)	Mr Alastair Williams (MQ)

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Ms Sarah Chamberlain (CU)		

Appendix 5: 2015 Publications

A FULL LIST OF CCFS PUBLICATIONS IS UPDATED AT: http://www.ccfs.mq.edu.au/

331. **O'Neill, C.**, Lenardic, A. and Condie, K.C. 2015. Earth's punctuated tectonic evolution: Cause and effect. In *N.M.W. Roberts, M. Van Kranendonk, S. Parman, S. Shirey, and P.D. Clift (eds)*, *Continent Formation Through Time*, *The Geological Society of London*, *389*, *17-40*.

346. **Mole, D.R.**, **Fiorentini, M.L.**, Cassidy, K.F., **Kirkland, C.L.**, **Thebaud, N.**, **McCuaig, T.C.**, Doublier, M.P., Duuring, P., Romano, S.S., Maas, R., **Belousova, E.A.**, Barnes, S.J. and Miller, J. 2015. Crustal evolution, intra-cratonic architecture and the metallogeny of an Archaean craton. In *G.R.T. Jenkin, P.A.J. Lusty, I. McDonald, M.P. Smith, A.J. Boyce and J.J. Wilkinson (eds)*, *Ore Deposits in an Evolving Earth*, *Geological Society of London Special Publication*, *393*, *Geological Society*, *23-80*.

348. **González-Jiménez**, **J.M.**, **Locmelis**, **M.**, **Belousova**, **E.**, **Griffin**, **W.L.**, Gervilla, F., Kerestedjian, T.N., **O'Reilly**, **S.Y.**, **Pearson N.J.** and Sergeeva I. 2015. Genesis and tectonic implications of podiform chromitites in the metamorphosed ultramafic massif of Dobromirtsi (Bulgaria). *Gondwana Research*, *27*, *555-574*.

380a. **Van Kranendonk, M.J.**, **Kirkland, C.L.** and **Cliff, J.** 2015. Oxygen isotopes in Pilbara Craton zircons support a global increase in crustal recycling at 3.2 Ga. *Lithos*, *228-229*, *90-98*.

382. Yang, Z.M., **Lu, Y.J.**, Hou, Z.Q. and Chang, Z.S. 2015. High-Mg diorite from Qulong in southern Tibet: Implications for the genesis of adakite-like intrusions and associated porphyry Cu deposits in collisional orogens. *Journal of Petrology*, 56, 227-254.

383. Hou, Z.Q., Yang, Z.M., **Lu, Y.J.**, Geng, Q.R., Yang, Z.S., Tang, J.X., Qu, X.M., Duan, L.F. and Zheng, Y.C. 2015. A genetic linkage between subduction- and collision-related porphyry Cu deposits in continental collision zones. *Geology*, *43*, *247-250*.

391. Angerer, T., Duuring, P., Hagemann, S., Thorne, W. and **McCuaig, T.C.** 2015. A mineral system approach to iron ore in Archaean and Paleoproterozoic BIF of Western Australia. In *G.R.T. Jenkin, P.A.J. Lusty, I. McDonald, M.P. Smith, A.J. Boyce and J.J. Wilkinson (eds)*, *Ore Deposits in an Evolving Earth*, *Geological Society of London Special Publication*, *393*, *81-115*.

441. Smithies, R.H., **Kirkland, C.L.**, Korhonen, F.J., Aitken, A.R.A., Howard, H.M., Maier, W.D., **Wingate, M.T.D.**, Quentin de Gromard, R. and **Gessner, K.** 2015. The Mesoproterozoic thermal evolution of the Musgrave Province in central Australia - plume vs. the geological record. *Gondwana Research*, *27*, *1419-1429*.

444. **Taneja, R.**, **O'Neill, C.**, **Lackie, M.**, **Rushmer, T.**, Schmidt, P. and Jourdan, F. 2015. $^{40}Ar/^{39}Ar$ geochronology and the paleoposition of Christmas Island (Australia), Northeast Indian Ocean. *Gondwana Research*, *28*, *391-406*.

453. Li, J., Zhao, P.P., Liu, J.G., **Wang, X.C.**, Yang, Y.A., Wang, G.Q. and Xu, J.F. 2015. Reassessment of hydrofluoric acid desilicification in the Carius tube digestion technique for Re-Os isotopic analysis in geological samples. *Geostandards and Geoanalytical Research*, *39*, *17-30*.

459. Dongre, A.N., **Jacob, D.E.** and Stern, R.A. 2015. Subduction-related origin of eclogite xenoliths from the Wajrakarur kimberlite field, Eastern Dharwar craton, Southern India: Constraints from petrology and geochemistry. *Gondwana Research*, *166*, *165-188*.

461. **Pisarevsky, S.A.**, De Waele, B., Jones, S., Söderlund, U. and Ernst, R.E. 2015. Paleomagnetism and U-Pb age of the 2.4 Ga Erayinia mafic dykes in the south-western Yilgarn, Western Australia: paleogeographic and geodynamic implications. *Precambrian Research*, *259*, *222-231*.

463. **Le Vaillant, M.**, Barnes, S.J., Miller, J., **McCuaig, T.C.**, Mucilli, P. and **Fiorentini, M.L.** 2015. A hydrothermal Ni-As-PGE geochemical halo around the Miitel nickel sulfide deposit, Yilgarn Craton, Western Australia. *Economic Geology*, *110*, *505-530*.

468. Condie, K., **Pisarevsky, S.A.**, Korenaga, J. and Gardoll, S. 2015. Is the rate of supercontinent assembly changing with time? *Precambrian Research*, *259*, *278-289*.

469. **Yao, W.-H.**, **Li, Z.-X.** and Li, W.-X. 2015. Was there a Cambrian ocean in South China? - Insight from detrital provenance analyses. *Geological Magazine*, *152*, *184-191*.

474. Fu, L., Wei, J., Chen, H., **Bagas, L.**, Tan, J., Li, H., Zhang, D. and Tian, N. 2015. The relationship between gold mineralization, exhumation of metamorphic core complex and magma cooling: Formation of the Anjiayingzi Au deposit, northern North China Craton. *Ore Geology Reviews*, *73*, *222-240*.

479. Jiang, S.-H., **Bagas, L.** and Liang, Q.-L. 2015. New insights into the petrogenesis of volcanic rocks in the Shanghang Basin in the Fujian Province, China. *Journal of Asian Earth Sciences*, *105*, *48-67*.

489. Yang, J., Meng, F., Xu, X., Robinson, P.T., Dilek, Y., Makeyev, A.B., Wirth, R., Wiedenbeck, M., **Griffin, W.L.** and **Cliff, J.** 2015. Diamonds, native elements and metal alloys from chromitites of the Ray-Iz ophiolite of the Polar Urals. *Gondwana Research*, *27*, *459-485*.

492. **Van Kranendonk, M.J.**, Smithies, R.H., **Griffin, W.L.**, Huston, D.L., Hickman, A.H., Champion, D.C., Anhaeusser, C.R. and Pirajno, F. 2015. Making it thick: a volcanic plateau origin of Palaeoarchean continental lithosphere of the Pilbara and Kaapvaal cratons. In *N.M.W. Roberts, M. Van Kranendonk, S. Parman, S. Shirey, and P.D. Clift (eds)*, *Continent Formation Through Time, Geological Society of London Special Publications, 389, 83-111 (2).*

494. Xiao, K., Li, N., Alok, P., Holden, E.-J., **Bagas, L.**, **Lu, Y.-J.** and Ying, L. 2015. GIS-based 3D Prospectivity Mapping: A Case Study of Jiama Copper-Polymetallic Deposit in Tibet, China. *Ore Geology Reviews*, *71*, *611-632*.

497. Howard, H.M., Smithies, R.H., **Kirkland, C.L.**, Kelsey, D.E. Aitken, A., **Wingate, M.T.D.**, Quentin de Gromard, R., Spaggiari C.V. and Maier, W.D. 2015. The burning heart - The Proterozoic geology and geological evolution of the west Musgrave Region, central Australia. *Gondwana Research*, *27*, *64-94*.

498. Roberts, N.M.W., **Van Kranendonk, M.J.**, Parman, S. and Clift, P. 2015. Continent formation through time. In *N.M.W. Roberts, M. Van Kranendonk, S. Parman, S. Shirey and P.D. Clift (eds)*, *Continent Formation Through Time*, *Geological Society of London Special Publications*, *389*, *1-16*.

499. **Van Kranendonk, M.J.** and Mazumder, R. 2015. Two Paleoproterozoic glacio-eustatic cycles in the Turee Creek Group, Western Australia. *Geological Society of America Bulletin*, *127*, *596-607*.

500. **Van Kranendonk, M.J.**, Mazumder, R., Yamaguchi, K., Yamada, K. and Ikehara, M. 2015. Sedimentology of the Paleoproterozoic Kungarra Formation, Turee Creek Group, Western Australia: A conformable record of the transition from early to modern Earth. *Precambrian Research*, *256*, *314-343*.

501. **Gardner, R.**, **Daczko, N.R.**, Halpin, J.A. and Whittaker, J.M. 2015. Discovery of a microcontinent (Gulden Draak Knoll) offshore Western Australia: implications for East Gondwana reconstructions. *Gondwana Research*, *28*, *1019-1031*.

501a. **Czaplińska, D.**, **Piazolo, S.** and Zibra, I. 2015. The influence of phase and grain size distribution on the dynamics of strain localization in polymineralic rocks. *Journal of Structural Geology*, *72*, *15-32*.

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Appendix 6: 2015 Abstract titles

A FULL LIST OF CCFS ABSTRACTS FOR CONFERENCE PRESENTATIONS IS AVAILABLE AT: http://www.ccfs.mq.edu.au/

4th Australasian Universities Geoscience Educators Network (AUGEN) Meeting, Melbourne, Victoria, Australia, 12-13 January 2015	Using a Virtual Petrographic Microscope in undergraduate teaching **N.R. Daczko**
ASEG-PESA 24th International Geophysical Conference and Exhibition, Perth, Australia, 15-18 February 2015	A major geophysical experiment in the Capricorn Orogeny, Western Australia A. Aitken, S. Banasazczyk, M. Dentith, M. Lindsay, J. Shragge, P. Piña-Varas, D. Annetts, J. Austin, Y. Ley-Cooper, T. Monday, B. Kennett, R. Murdie and **H. Yuan** Geoscience data integration: Insights into mapping lithospheric architecture G.C. Begg, **W.L. Griffin**, **S.Y. O'Reilly** and **L. Natapov** **Keynote**
13th Biennial AMAS Symposium, Hobart, Australia, 11-13 February 2015	Quantitative microstructural analysis of geological materials: New views on glacier flow, meteorite impacts and deep mantle processes **S. Piazolo** **Invited**
WA Geophysics Workshop, Perth, Australia, 18 February 2015	Large scale issues in the WA lithosphere **H. Yuan** **Invited**
46th Lunar and Planetary Science Conference, The Woodlands, TX, USA, 16-20 March 2015	REE and Ti in lunar zircons reflect temperature and oxygen fugacity of lunar magmas? **M. Grange**, **A.A. Nemchin**, M.J. Whitehouse and R.E. Merle
Chinese Academy of Sciences (IGG-CAS), Beijing, China, 30 March 2015	Seismic jigsaw of the Western Australian Craton and insights into early Archean crust formation tectonics, Institute of Geology and Geophysics **H. Yuan**
European Geosciences Union (EGU), Vienna, Austria, 12-17 April 2015	Decarbonation of subducting slabs: insight from thermomechanical-petrological numerical modeling **C.M. Gonzalez**, **W. Gorczyk** and T. Gerya Databases related to Large Igneous Provinces R.E. Ernst and **S.A. Pisarevsky** Age and paleomagnetism of the Precambrian Listvyanka dyke swarm (South Siberia): implications for Nuna and Rodinia **S.A. Pisarevsky**, D.P. Gladkochub, R.E. Ernst, T.V. Donskaya, M. Hamilton, A.M. Mazukabzov, K. Konstantinov and A.M. Stanevich Hydration through melt-rock interaction triggers local partial melting in the lower crust: Example from Fiordland, New Zealand **C. Stuart**, **S. Piazolo** and **N. Daczko** Multi-stage supra-subduction metasomatism in the Cabo Ortegal Complex, Spain **R. Tilhac**, **S.Y. O'Reilly**, **W.L. Griffin**, **N.J. Pearson**, G. Ceuleneer and M. Grégoire Estimation of uncertainties in a 3D geological model of the Sandstone Greenstone Belt, Yilgarn Craton, Western Australia F. Wellmann, R. Murdie and **K. Gessner**

2015 Joint Assembly: Canadian Cratons Through Time: 4.0 Ga of Chemical Evolution and Tectonism, Montreal, Canada, 3-6 May 2015	Using U-Pb, Lu-Hf and O Isotopes in zircons to unlock the crust-mantle evolution and relationships to mineral systems of the Marmion Terrane (3.02-2.68 Ga), Superior Province, Canada **K.E. Björkman**, **Y.J. Lu**, **T.C. McCuaig** and P. Hollings
AGU-GAC-MAC Joint Assembly, Montreal, Canada, 3-7 May 2015	The Large Igneous Provinces Industry Consortium Project: Accomplishments and next steps R.E. Ernst, W. Bleeker, U. Söderlund, M.A. Hamilton, K. Chamberlain, P.J. Sylvester, **M.T.D. Wingate**, **S.A. Pisarevsky**, B. Cousens, P.N. Hollings, A.C. Kerr and S.M. Jowitt Supercontinent-superplume coupling in Earth history: toward a new tectonic paradigm **Z.X. Li** Paleoproterozoic paleogeographic reconstructions: Based on paleomagnetic data and lips barcode constraints. **S.A. Pisarevsky** and R.E. Ernst
WA, Multiscale Seismic Workshop, ARRC, Perth, Australia, 19 May 2015	Passive seismic studies in the Capricorn orogen **H. Yuan** **Invited**
Astrobiology Science Conference 2015, Habitability, Habitable Worlds and Life, Chicago, USA, 15-19 June 2015	The evidence for hydrothermal formation of talc-carbonate at Nili Fossae and implications for astrobiology on Mars A.J. Brown, C. Viviano-Beck, J.L. Bishop, N.A. Cabrol, D. Anderson, P. Sobron, J. Moersch, **M. Van Kranendonk** and M.J. Russell SIMS $\delta^{18}O$ of stromatolitic cherts and sandstones in the 3.4 Ga Strelley Pool Formation: implications for PaleoArchean $\delta^{18}O$ values J.N. Cammack, M.J. Spicuzza, **M.J. Van Kranendonk**, A.H. Hickman, R. Kozdon, A.J. Cavosie and J.W. Valley Microstructure-specific carbon isotopic signature of organic matter supports biologic origin in ~3.5 Ga cherts of the Pilbara Craton N. Morag, K.H. Williford, K. Kitajima, P. Philippot, **M.J. Van Kranendonk**, K. Lepot and J.W. Valley Early Archean carbonates on Early Earth - Microbial biosignature versus hydrothermal origin J. Reitner, J.-P. Duda, N. Schäfer, M. Hoppert and **M.J. Van Kranendonk** The elements of life at a 3.5 Ga subaerial hotspring: Evidence from the Dresser Formation, Pilbara Craton, Australia **M.J. Van Kranendonk**, T. Djokic, G. Poole and E. Nakamura
World Chinese Geoscience Conferences, Academia Sinica, Taipei, Taiwan, 15-21 June 2015	Supercontinent-superplume coupling in Earth history: toward a new tectonic paradigm **Z.X. Li** **Invited**
Inaugural Advanced Resource Characterisation Facility Conference, Perth, Australia, 18 June 2015	High-impact atom probe research: A case study on shocked zircon **S.M. Reddy** **Invited** The NRSP's geoscience atom probe: Context and future research **S.M. Reddy** **Invited**
78th Annual Meeting of the Meteoritical-Society, Berkeley, CA, USA, 27-31 July 2015	Characterising the role of mineral orientation on IR microspectroscopy G.K. Benedix, V.E. Hamilton and **S.M. Reddy** New Pb-isotopic constraints on the age of the moon J.F. Snape, **A.A. Nemchin**, J.J. Bellucci, M.J. Whitehouse, R. Tartese, J.J. Barnes, M. Anand, I.A. Crawford and K.H. Joy Record of the early impact history of the Earth-Moon system: targeted geochronology of shocked zircon N.E. Timms, **S.M. Reddy**, A.J. Cavosie, **A.A. Nemchin**, **M.L. Grange** and T.M. Erickson **Invited**

Microscopy and Microanalysis 2015, Portland, USA, 2-6 August 2015	Solving the controversy of Earth's Oldest Fossils using electron microscopy **D. Wacey**, M. Saunders, C. Kong and M. Brasier
Saying goodbye to a 2D Earth, International Conference, Margaret River, WA, Australia, 2-7 August 2015	The future of 3D modeling in Geological Surveys **K. Gessner**, R.E. Murdie, L. Brisbout, **H. Yuan**, and C. Sippl A 3D fault model of the NW Yilgarn R.E. Murdie, T. Ivanic, I. Zibra and **K. Gessner** The Capricorn Orogen Passive Source Array R.E. Murdie, **H. Yuan**, M. Denith, S. Johnson, J. Brett and **K. Gessner**
12th Annual Meeting Asia Oceania Geosciences Society (AOGS), Singapore, 2-7 August 2015	The effect of crustal heterogeneities on the formation of Dabashan Orocline and the growth of the Tibetan Plateau: Evidence from ambient noise tomography C. Jiang, **Y. Yang** and Y. Zheng Imaging lithospheric structures using broadband surface waves from ambient noise **Y. Yang** Heterogeneous crust in the Western Australian Craton: Seismic characteristics and tectonic implications **H. Yuan** **Invited**
IGCP-649 Workshop on: Ophiolites and Related High-Pressure Rocks in the Qilian Mountains, Xining, China, 5-10 August 2015	Transition-zone mineral assemblages in peridotite massifs, Tibet: Implications for collision-zone dynamics and orogenic peridotites **W.L. Griffin**, **N.M. McGowan**, J.M. Gonzalez-Jimenez, **E.A. Belousova**, D. Howell, **J.C. Afonso**, J.S. Yang, R. Shi, **S.Y. O'Reilly** and **N.J. Pearson** Ophiolitic chromitites originated from ancient SCLM R.D. Shi, **W.L. Griffin**, **S.Y. O'Reilly**, Q.S. Huang, D.L. Liu, X.H. Gong, S.S. Cheng, K. Wu and G.D. Yi Diamonds and highly reduced minerals from chromitite of the Ray-Iz Ophiolite of the Polar Urals: Deep origin of podiform chromitites and ophiolitic diamonds J.S. Yang, R. Wirth, M. Wiedenbeck, **W.L. Griffin**, F.C. Meng, S.Y. Chen, W.J. Bai, X.X. Xu, A.B. Makeeve and N.I. Bryanchanliniova
2015 Goldschmidt Conference, Prague, Czech Republic, 16-21 August 2015	Crystal/melt partitioning of volatile and non-volatile elements during peridotite melting: Implications for mantle fractionation **J. Adam**, M. Turner, E. Hauri and **S. Turner** The genesis of silicic magmas in shallow crustal cold zones **J. Adam**, **S. Turner** and **T. Rushmer** Low-Ni olivine from silica-undersaturated ultrapotassic rocks as evidence for carbonate metasomatism in the mantle E. Ammannati, **D.E. Jacob**, R. Avanzinelli, **S.F. Foley** and S. Conticelli Mg and Fe isotope geochemistry of garnet peridotites from the Kaapvaal and Siberia Cratons Y. An, F. Huang, **J. Huang**, **W.L. Griffin** and C. Liu Magmatic controls on the genesis of Ni-Cu±(PGE) sulphide mineralisation on Mars **R.J. Baumgartner**, **M.L. Fiorentini**, D. Baratoux, S. Micklethwaite, A.K. Sener, J.P. Lorand and **T.C. McCuaig** The impact of subducted slab components on back-arc melting C. Beier, **S. Turner**, M. Regelous and K. Haase Towards a coherent radiogenic isotopic model for Mars J.J. Bellucci, **A. Nemchin**, M. Whitehouse and J. Snape A cautionary tale on zircon ages from mafic-ultramafic rocks: a case example from ophiolites, SE Australia **E. Belousova**, J.-M. González-Jiménez, I. Graham, **W. Griffin**, **S.Y. O'Reilly** and **N. Pearson** Age and hafnium isotopic evolution of the Western Ethiopian Shield M. Blades, A. Collins, J. Foden, J. Payne, T. Alemu, G. Woldetinsae, **C. Clark** and R. Taylor Geochronology of ex situ shocked zircons: Towards dating impacts A.J. Cavosie, **S.M. Reddy**, N.E. Timms, T.M. Erickson and M.R. Pincus **Invited**

2015 Goldschmidt Conference, Prague, Czech Republic, 16-21 August 2015 *cont...*

Thermodynamic modelling of the mobility of minor and trace elements in metamorphosed chromites
V. Colás, J.M. González-Jiménez, I. Fanlo, **W.L. Griffin**, F. Gervilla, **S.Y. O'Reilly**, **N.J. Pearson** and T. Kerestedjian

Subducting the Mozambique Ocean: Cryogenian arc formation throughout the East African Orogen
A.S. Collins, D. Archibald, M. Blades, F. Robinson, D. Plavsa, J. Foden, **S. Pisarevsky**, **C. Clark** and R. Taylor

Laser ablation *in situ* (U-Th-Sm)/He and U-Pb double dating of apatite
M. Danišík, B. McDonald, N. Evans, B. McInnes, **C. Kirkland** and T. Becker

To subduct or not to subduct? That is the Archaean question…
V. Debaille, **C. O'Neill** and A.D. Brandon **Invited**

Eclogite xeoliths with subducted oceanic crust signatures from the Wajrakarur Kimberlites, Southern India: evidences from trace element and O isotope geochemistry
A. Dongre, **D. Jacob**, R. Stern and F. Viljoen

Geobiology of an exceptionally preserved Archean microbial mat facies (Strelley Pool Formation, Western Australia)
J.-P. Duda, V. Thiel, M. Blumenberg, D. Ionescu, N. Schäfer, **M.J. Van Kranendonk** and J. Reitner

Iron-mineralized microfossils from the Great Oxygenation Event
A. Fadel, K. Lepot, V. Busigny, A. Addad and **M.J. Van Kranendonk**

Magmatic processes at persistently active arc volcanoes
C. Firth, **S. Turner**, M. Turner, S. Cronin and **H. Handley**

The important role of incipient melting in the compositional and petrological evolution of the mantle
S. Foley and G. Yaxley

From MARID to lamproite: melting phase relations of MARID-like xenoliths from Kimberley, South Africa
M.W. Förster, D. Prelevic, H.R. Schmück, S. Buhre S and **D.E. Jacob**

Timescales of magma transfer, degassing and crustal assimilation at Merapi Volcano, Indonesia
R. Gertisser, **H. Handley**, M. Reagan, K. Preece, K. Berlo, J. Barclay and R. Herd **Invited**

HP-HT metasomatic garnetite associated with lherzolite complexes in the Urals: An indicator of timing of mantle upwelling and exhumation
I. Gottman, E. Pushkarev and **E. Belousova**

New insights into the lithospheric and deeper mantle
W.L. Griffin, **J.C. Afonso**, **T. Satsukawa**, **N. McGowan**, **N. Pearson** and **S.Y. O'Reilly** **Invited**

Modeling microstructural disequilibria during generation of oceanic basalts
C. Grose and **J.C. Afonso**

Constraints from Sr-Nd-Hf-Pb-Os isotopes for enriched and depleted Hawaiian Plume components in the oldest Emperor Seamounts
K. Hoernle, **B. Schaefer**, M. Portnyagin, F. Hauff and R. Werner **Invited**

Mg isotopes in Roberts Victor xenolithic eclogites: no crustal origin
J.-X. Huang, **W. Griffin**, Y. Xiang, L. Xie, **N. Pearson** and **S.Y. O'Reilly**

Nanostructure of Arctica islandica Shells: Implications for formation pathways
D. Jacob, R. Wirth, **S. Piazolo** and P. Trimby

LASS-ICPMS zircon geochronology: comparisons with SHRIMP
I. Jahn, **C. Clark**, **S.M. Reddy**, R. Taylor and A. Kylander-Clark

Metallic lead nanospheres discovered in ancient Antarctic zircons
M. Kusiak, D. Dunkley, M. Whitehouse, **S. Wilde**, R. Wirth and K. Marquardt **Invited**

Extrapolating regolith geochemical data for regional analysis of the critical layer using ASTER remote sensing data
H. Lampinen

Probing the record of mantle processes and crust-mantle interactions in minerals, rocks and their geochemical properties
N. Liptai

Geochemical signatures of spinel peridotite xenoliths from the northernmost locations of the Pannonian Basin
N. Liptai, **S.Y. O'Reilly**, **W.L. Griffin**, **N.J. Pearson** and C. Szabó

2015 Goldschmidt Conference, Prague, Czech Republic, 16-21 August 2015 *cont...*

Zircon multi-isotopic mapping: Imaging lithospheric architecture and continental crust evolution
Y. Lu, T. Kemp, **T.C. McCuaig** and Z. Hou

Composition and characterisation of chromites, alloys and sulphide inclusions from the Indo-Myanmar Ophiolite Belt of northeastern India
B. Maibam, **S.F. Foley**, **D.E. Jacob**, T.B., Singh, D. Ray and D. Panda

Integration of electron, laser and ion microprobe techniques to create an open source digital mineral library of Western Australia
B. McInnes, A. Brown, N. Evans, N. McNaughton and **M. Wingate**

The individuality of ascent paths in small volcanic systems: Small eruptive centres near Villarrica Volcano, Chile
L. McGee, E. Morgado, **H. Handley**, M. Turner, L.E. Lara, R. Brahm and M.A. Parada

Quantitative microstructural and trace element geochemical analysis of a mineralogically zoned vein
H. Meadows, **S. Reddy**, **C. Clark** and R. Taylor

In situ U-Pb zircon dating on metapelitic granulites of Beni Bousera (Betico-Rifean Belt, N Morocco)
M. Melchiorre, A. Álvarez-Valero, M. Fernàndez, J. Vergés, **E. Belousova**, A. El Maz and A. Moukadiri

Pro- and retrograde igneous activity during the Neoarchaean Skjoldungen Orogeny in the SE Greenland
T. Næraa, **L. Bagas**, J. Tusch, T.F. Kokfelt and C. Münker

The evolution of the Hadean Earth
C. O'Neill **Keynote**

Variations in intraplate melting regimes during Earth's Evolution
C. O'Neill and **S. Zhang** **Invited**

Cratons, metasomatism and metallogeny
S.Y. O'Reilly, **W. Griffiin**, **N. Pearson**, G. Begg and **J. Hronsky** **Invited**

Zircon Hf- and O-Isotope constraints on the evolution of the Paleoproterozoic Baoulé-Mossi domain of the West African Craton
L.A. Parra, **M.L. Fiorentini**, **E. Belousova**, A.I.S. Kemp, J. Miller and **T.C. McCuaig**

U-Pb geochronology of zircon by femtosecond laser ablation
N. Pearson, **W. Powell**, **Y. Gréau**, **R. Murphy**, J. Payne, **E. Belousova**, **W. Griffin** and **S.Y. O'Reilly**

Multidisciplinary study of a recent oceanic pluton: The syenitic complex of Rallier du Baty, Kerguelen (TAAF)
L. Ponthus, D. Guillaume, M. SaintBlanquat, M., Benoit, **N. Pearson**, M. Gregoire, **S.Y. O'Reilly** and M. LeRomancer

Making new felsic crust in primitive arc settings: Contrasting case studies
T. Rushmer, **S. Foley**, **R. Brens**, **J. Adam** and **S. Turner**

Mantle wedge heterogeneties recorded by microstructural evolution
T. Satsukawa, T. Mizukami, T. Morishita, **W.L. Griffin**, **S.Y. O'Reilly** and K. Michibayashi

Os isotope evidence for a heterogeneous source for the world's largest phanerozoic volcanic event
B. Schaefer, K. Hoernle, I. Parkinson, R. Golowin, M. Portnyagin, **S. Turner**, F. Hauff and R. Werner

Analytical and experimental study of post-collisional volcanism in the Alpine-Himalayan belt
D. Prelević, H.R. Schmück, S. Buhre, **Y. Wang** and **S. Foley**

Linking mineralization, isotopic composition, chemical composition and pyrite textures in the Neoarchaean Paulsens Au deposit
V. Selvaraja, **M. Fiorentini**, **C. LaFlamme**, **H. Jeon** and B. Wing

Mass independent sulfur signature in Archean orogenic Au deposits
V. Selvaraja, **M. Fiorentini**, **C. LaFlamme**, B. Wing, T.H. Bui and I. Fielding

Manganese speciation in bivalve shell aragonite
A. Soldati, **D.E. Jacob**, P. Glatzel, J. Grattage and J. Geck

C-isotopes of diamonds in eclogites from the Nyurbinskaya Pipe, Yakutia: Evidence for metasomatic origin
Z. Spetsius, **W. Griffin** and **S.Y. O'Reilly**

Rare earth element partition coefficients during high-grade metamorphism: Experiments, realities, and large datasets
R. Taylor, **C. Clark**, P. Kinny and A. Kylander-Clark

2015 Goldschmidt Conference, Prague, Czech Republic, 16-21 August 2015 *cont...*	Metasomatized segregates of high-Ca boninites: Cabo Ortegal Pyroxenites **R. Tilhac**, M. Grégoire, G. Ceuleneer, **S.Y. O'Reilly**, **W.L. Griffin** and **N.J. Pearson** Crustal evolution of the Markha Terrane, Siberian Craton: Evidence from U-Pb, Hf- and O-isotope data for zircons from the Nakyn Kimberlites **I. Tretiakova**, **E. Belousova**, **W. Griffin**, V. Malkovets and **N.J. Pearson** The Tonga-Kermadec arc - Lau back-arc: recent progress and future research directions **S. Turner** **Keynote** Maturity of Archean sandstones and ancient detrial zircons J.W. Valley, M.J. Spicuzza, J.N. Cammack, K. Kitajima, N.T. Kita and **M.J. Van Kranendonk** Identifying the origin of olivines in ultramafic lamprophyres from Labrador, Canada, by minor and trace elements M. Veter, **S. Foley** and D. Prelevic Composition of the lithospheric mantle beneath the Khamar Daban Ridge, South Russian Siberia: Constraints from mantle xenoliths **K.L. Wang**, S. D'rill, **S.Y. O'Reilly**, M. Kuzmin, **W.L. Griffin** and **N.J. Pearson** Lawsonite blueschists in recycled mélange involved in K-rich orogenic magmatism **Y. Wang**, D. Prelević, **S. Foley**, S. Buhre and S. Galer Estimating atmospheric lead concentrations and isotopic composition using two Lichen Genera over the past 120 years in Australia L. Wu, M. Taylor, **H. Handley** and M. Wu Two-layered Neo-Tethyan oceanic lithospheric mantle in a Tibetan ophiolite, China **Q. Xiong**, **W.L. Griffin**, **S.Y. O'Reilly**, **N.J. Pearson** and J.P. Zheng
13th SGA Conference, Nancy, France, 24-27 August 2015	Linking crustal evolution to mineral systems using U-Pb geochronology in zircons from the Marmion Terrane (3.02-2.68 Ga), western Superior Craton, Canada **K.E. Björkman**, **T.C. McCuaig**, **Y.J. Lu**, P. Hollings and G.P. Beakhouse Sulfur cycle in the deep continental crust: insight from the Ni-Cu-PGE sulfide deposits of the Ivrea Zone (Italy) **M. Fiorentini**, G. Garuti, F. Zaccarini, P. Kolleger, **L. Martin** and **J. Cliff** Magmatic controls on the genesis of Ni-Cu±(PGE) sulphide mineralisation on Mars **R.J. Baumgartner**, **M.L. Fiorentini**, D. Baratoux, S. Micklethwaite, A.K. Sener, J.P. Lorand and T.C. McCuaig Hypozonal orogenic gold mineralisation: a Precambrian mineral system **J. Kolb**, A. Dziggel and **L. Bagas** Fluid flow and rock permeability considerations for Au mineral systems: inputs from numerical simulations **J. Poh**, **N. Thébaud**, M. Lindsay, **M. Fiorentini**, F. Wellmann and **P. Rey** Sulfur sources in the Glenburgh Orogenic Gold Deposit **V. Selvaraja**, **M.L. Fiorentini**, B. Wing, T.H. Bui, L. Roche, S. Occhipinti and J. Goldsworthy Evolution of the Siberian Craton lithosphere: evidence from U-Pb and Hf isotope data for zircons from kimberlites **I. Tretiakova**, **E. Belousova**, **W. Griffin**, **N. Pearson**, V. Malkovets and S. Kostrovitsky
2nd European Mantle Workshop, Wroclaw, Poland, 24-28 August 2015	Super-reducing conditions in the upper mantle beneath the lower Galilee (Israel) **W.L. Griffin**, **S.E.M. Gain**, V. Toledo, **D. Adams**, **S.Y. O'Reilly**, **D.E. Jacob** and **N.J. Pearson** Constraints on the geochemical properties and processes of the upper mantle beneath the northernmost part of the Pannonian Basin **N. Liptai**, **S.Y. O'Reilly**, **W.L. Griffin**, **N.J. Pearson** and C. Szabó Geodynamic and geophysical consequences of stealthy mantle metasomatism **S.Y. O'Reilly**, **W.L. Griffin** and **N.J. Pearson** **Invited**
Large Igneous Provinces, Mantle Plumes and Metallogeny in the Earth's History, Irkutsk-Listvyanka, Russia, 1-8 September 2015	Three stages of the intracontinental mafic magmatism in the south-eastern part of the Sharyzhalgai Inlier of the Siberian Cratonic basement D.P. Gladkochub, T.V. Donskaya, R.E. Ernst, **S.A. Pisarevsky** and A.M. Mazukabzov

8th Hutton Symposium on Granites and Related Rocks, Florianópolis, Brazil, 20-25 September 2015	Post-collisional Late Neoproterozoic high Ba-Sr granitic magmatism of adakitic affinity from the Dom Feliciano belt and its cratonic foreland, Uruguay **P. Lara**, P. Oyhantcabal and **K.A. Dadd** Neoproterozoic and Late Paleozoic granitoids of Wrangel Island and Central Chukotka: Age, composition and setting in the structure of Arctic Region M.V. Luchitskaya, S.D. Sokolov, S.A. Sergeev, A.B. Kotov, **L.M. Natapov**, **E.A. Belousova** and S.M. Katkov Petrogenesis of the 2.09 Ga Laouni granitic magmatic granite basement (central Hoggar, southern Algeria): *in-situ* zircon U-Pb age and Nd-Hf isotopic constraints N. Remaci-Benaouda, **E. Belousova**, **Y. Greau**, P. Bowden, J.Y. Cottin, D. Bouziani, **W.L. Griffin** and **S.Y. O'Reilly** Six-stage Mesozoic granitoids in an Andean-type orogenic cycle in South China K. Zhu, **Z. Li**, X. Xu, **S.A. Wilde** and H. Chen
First China-Russia International Meeting on the Central Asian Orogenic Belt and IGCP 592 Workshop, Beijing, China, 23-25 September 2015	The scenario of the Paleo-Asian Ocean development with focus on detrital zircon ages spectra in the Late Precambrian sediments of the Southern Siberian craton D.P. Gladkochub, T.V. Donskaya, S. Zhang, K.-L. Wang, **S.A. Pisarevsky**, A.M. Stanevich, A.M. Mazukabzov and Z. Motova
TIGeR Conference, Curtin University, Perth, Australia, 23-25 September 2015	Geologic applications for high-resolution secondary ion mass spectrometry (SIMS) to study fluid-rock interaction **H. Jeon**, **C. LaFlamme**, **L. Martin**, **M. Kilburn**, J. Cliff and **M. Fiorentini** The chemical signature of syn-deformational fluid-rock interaction: Nano- to microscale **S. Piazolo** **Invited** A shocking transformation: probing Precambrian reidite using state of-the-art micro- to sub-nanometer 3D imaging. Key issues in fluid-rock interaction: From the nano to the macroscale **S.M. Reddy**, T.E. Johnson, W. Rickard, A. van Riessen, R.J.M. Taylor, D.W. Saxey, D. Fougerouse, S. Fischer, T.J. Prosa, D.A. Reinhard, K.P. Rice and Y. Chen Hydration through melt-rock interaction triggers local partial melting in the lower crust: Example from Fiordland, New Zealand **C. Stuart**, **S. Piazolo** and **N. Daczko**
SEG 2015: World-Class Ore Deposits: Discovery to Recovery, Hobart, Australia, 27-30 September 2015	Massive chalcopyrite mineralization at Red Bore, WA: The deep roots of a sea-floor hydrothermal system A. Agangi, C. Vieru, **S. Reddy**, D. Plavsa and **V. Selvaraja** Linking crustal growth to orogenic gold and Ni-Cu-PGE mineralization using U-Pb geochronology in zircons in the Marmion Terrane (3.0 Ga), Western Superior Craton, Canada **K. Bjorkman**, **Y. Lu** and **T. Campbell** Stratigraphy-controlled minero-chemical and isotopic imprints for primary sulfur degassing of lavas in komatiite-hosted Ni-PGE ores at Wannaway deposit, Western Australia **S. Caruso**, M. Moroni, **M.L. Fiorentini**, S.J. Barnes, C. Carissa, B. Wing and J. Cliff In search of high flux magma conduits: 3D photogrammetry, analyzing emplacement mechanisms of mafic intrusion networks **G. Dering**, S. Micklethwaite, **M. Fiorentini**, S. Barnes and A. Cruden The spatial and temporal significance of alteration associated with gold-bearing structures in the Greater Revenge Area, St. Ives, Western Australia B.M. Duggan, **T.C. McCuaig** and J.M. Miller High-K to shoshonitic magmatism across the northern Archean Kéména Man margin (Guinea): Implications for the late Eburnean orogenic gold mineralization A. Eglinger, **N. Thébaud**, J. Davis, J. Miller, A. Zeh, **T.C. McCuaig** and **E. Belousova** Sulfur and metal fertilization of the lower continental crust **M.L. Fiorentini**, M. Locmelis, **J. Adam**, **T. Rushmer**, F. Zaccarini, G. Garuti, Z. Vukmanovic, **S. Caruso**, M. Moroni, S. Barnes, **S. Reddy** and B. Godel **Invited** Postorogenic Paleoproterozoic mafic intrusions within the Rae Craton **C. LaFlamme**, D. Lentz and C. McFarlane

SEG 2015: World-Class Ore Deposits: Discovery to Recovery, Hobart, Australia, 27-30 September 2015 *cont...*	Mapping mineral systems footprints THROUGH cover - linking remote and proximal surface geochemical and mineralogical data to bedrock geology **H. Lampinen**, C. Laukamp, S. Halley, L. Hardy, S. Occhipinti, **T.C. McCuaig** and **M. Fiorentini** Effects of hydrous alteration on the distribution of base metals and platinum group elements within the Kevitsa Magmatic Nickel Sulfide Deposit M. Le Vaillant, S.J. Barnes, **M.L. Fiorentini**, F. Santaguida and T. Törmänen High magmatic water content disproves genesis of post-collisional copper-ore-forming high Sr/Y magmas by dehydration melting of lower crust **Y.J. Lu**, **R.R. Loucks**, **M.L. Fiorentini**, Z.M. Yang, Z.M. and Z.Q. Hou Petrochemistry of the Ntaka Hill Mafic-Ultramafic Intrusion and implications for Ni-Cu mineralization **D.R. Mole**, S.J. Barnes and M. Campbell The Formation of the Ntaka Hill Ni-Cu Deposit: Plume magmas captured by an Island Arc **D.R. Mole**, R. Taylor, P. Kinny and S.J. Barnes Evidence for fluid- and gas-driven magmatic Ni-Fe-Cu-PGE-rich sulfide ore deposition associated with mantle metasomatism in the Valmaggia ultramafic pipe, Ivrea-Verbano, Italy M. Moroni, **M.L. Fiorentini**, **S. Caruso**, M.L. Frezzotti and G. Sessa Trace element variations in TiO_2 due to polymorphism and age: Implications for rutile as a pathfinder mineral in complex terranes D. Plavsa, **S. Reddy**, **C. Clark** and A. Kylander-Clark Using TiO_2 as pathfinder for mineralized ore systems: A combined EBSD and petrochronology approach D.S. Plavsa, **S. Reddy**, **C. Clark** and A. Kylander-Clark Crustal architecture and under cover exploration: The Granites-Tanami orogen example **D. Stevenson**, **L. Iaccheri**, **L. Bagas**, **C. McCuaig** and A. Aitken *In situ* sulfur isotopes from mineral systems in the Proterozoic Capricorn Orogen **S. Vikraman**, **C. LaFlamme**, **M. Fiorentini** and **H. Jeon**
15th Australian Space Research Conference, Canberra, ACT, Australia, 29 September - 1 October 2015	The role of core-differentiation in ejection of a Moon-forming disk **C. O'Neill** and **S. Zhang** Dating late thermal events on the Moon from the annealing of radiation damage in zircon **R.T. Pidgeon**, R.E. Merle, **M.L. Grange** and **A.A. Nemchin** Early Earth and the making of Mankind: Astrobiology in our own backyard **M.J. Van Kranendonk** **Plenary Speaker** Viscosity formulations and the effect of uncertain parameters **J. Wasiliev**, **C. O'Neill** and **S. Zhang** Thermal evolution of the Moon modelled by core-mantle coupling **S. Zhang** and **C. O'Neill**
Geological Society of America Meeting, Baltimore, Maryland, USA, 1-4 November 2015	Revisiting the impact chronology of the Moon: a terrestrial perspective on using ex situ shocked zircons to date meteorite impacts A.J. Cavosie, T.E. Erickson, N.E. Timms, **S.M. Reddy**, C. Talavera, S.M. Montalvo, M.R. Pincus, R. Gibbon and D. Moser Growth of continental lithosphere by accretion of arc terranes along the Laurentian margin throughout the Proterozoic: evidence from Hf isotopes M.E. Holland, K.E. Karlstrom, M.F. Doe, T.A. Grambling, E.G. Gehrels, E. George, M. Pecha, **W.L. Griffin**, **E. Belousova**, G.C. Begg and C.A. Mako Precambrian reidite unearthed **S.M. Reddy**, T. Johnson, W. Rickard, A. van Riessen, S. Fischer, R. Taylor, T. Prosa, D. Reinhard, K. Rice and Y. Chen **Invited**
2nd Lithosphere Dynamics Workshop, Perth, Australia, 19-20 November 2015	Ruthenium in spinel from Chassignite and olivine-phyric Shergottite meteorites: constraints on the behaviour of platinum-group elements and sulphur in Martian magmatic systems **R.J. Baumgartner**, **M.L. Fiorentini**, D. Baratoux, L. Ferrière, M. Locmelis and A.K. Sener Cassiterite as a multiprocess recorder in Sn bearing systems J. Bennett, A. Kemp, S.G. Hagemann and **M. Fiorentini**

2nd Lithosphere Dynamics Workshop, Perth, Australia, 19-20 November 2015	Unravelling crustal growth and geodynamics in the Meso to Neoarchaean using U-Pb-O isotopes in zircons and stratigraphic reconstructions from the Marmion Terrane (3.0 Ga) **K.E. Björkman**, **T.C. McCuaig**, **Y.J. Lu**, A.I.S. Kemp and P. Hollings Crust-mantle interactions in hot orogens characterised by counterclockwise P-T-t paths and slow cooling **M. Brown** **Invited** Sulfur and metal fertilization of the lower continental crust **M. Fiorentini** **Invited** Evolution of the lithospheric mantle by melt/rock interaction and its effects on the composition of lithosphere-derived volcanic melts **S. Foley** **Invited** Constraints on kimberlite ascent mechanisms revealed by phlogopite compositions in kimberlites and mantle xenoliths **A. Giuliani** **Invited** *in-situ* U-Pb, O and Hf isotopic compositions of detrital zircons from the North Australian Craton **L.M. Iaccheri** Neutral-buoyancy rule over-ruled: Crustal underplating by buoyant magmas during orogeny **R. Loucks** **Invited** Secular change in Archean crust formation recorded in Western Australia **H. Yuan** **Invited**
Specialist Group in Tectonics and Structural Geology (SGTSG) conference: Riding the Wave, Caloundra, Queensland, Australia, 22-27 November 2015	Arc root buoyancy: metastable igneous assemblages in deformed lower crust T. Chapman, G.L. Clarke and **N.R. Daczko** Undergraduate teaching with a Virtual Petrographic Microscope **N.R. Daczko** The Neoproterozoic East Gondwana suture: Reconciling geological and geophysical evidence **N.R. Daczko**, J.A. Halpin, J.M. Whittaker and **I.C.W. Fitzsimons** Does microstructure matter? Investigating the effect of spatial distribution of viscosity on bulk strength and strain localisation **R.L. Gardner**, **S. Piazolo**, L. Evans and **N.R. Daczko** Microcontinents offshore Western Australia: insights into the make-up and break-up of East Gondwana J.A. Halpin, **N.R. Daczko**, J.M. Whittaker, S.E. Williams, R.L. Gardner, M.E. Kobler and P.G. Quilty A new map of the Wongwibinda Metamorphic Complex: its relationship to other HTLP complexes of the New England Orogen **K. Jessop**, **N.R. Daczko** and **S. Piazolo** Steep metamorphic field gradients in HTLP regional aureoles **K. Jessop**, **N.R. Daczko** and **S. Piazolo** Supercontinent-superplume coupling and a new global geodynamic working model **Z.X. Li**
GSWA 2015 Annual Lectures, Perth, Australia, 3 December 2015	Inferring past and current tectonic activities using Earthquake seismology **H. Yuan** **Invited**
Greenland Day Conference, Perth, Australia, 9 December 2015	Nickel-sulfide ore forming processes in the deep continental crust, Thrym Complex, southeastern Greenland **M. Fiorentini** A window into Greenland's geological past: a new geochronology database with implications for mineral exploration **C. Kirkland** The Paleoproterozoic Karrat Group and Rinkian Belt: geology, Black Angel Zn-Pb deposit and other mineralization styles **J. Kolb**

Meeting	Abstracts
59th Annual Meeting of the Palaeontological Association, Cardiff, UK, 14-17 December 2015	Solving the controversy of Earth's oldest fossils using electron microscopy **D. Wacey**, M. Saunders, C. Kong and M. Brasier
AGU Fall Meeting, San Francisco, USA, 14-18 December 2015	Multi-observable thermochemical tomography of the lithosphere and upper mantle **J.C. Afonso**, **Y. Yang**, N. Rawlinson, A. Jones, J. Fullea and **M. Qashqai** Erosion and assimilation of substrate by Martian low-viscosity lava flows: implications for sulphur degassing and the genesis of orthomagmatic Ni-Cu-(PGE) sulphide mineralisation **R. Baumgartner**, D. Baratoux, F. Gaillard and **M.L. Fiorentini** Imaging anisotropic layering with Bayesian Inversion of multiple data types T. Bodin, J. Leiva, B. Romanowicz, V. Maupin and **H. Yuan** Were Amazonia and Baltica connected in Nuna and Rodinia? S.V. Bogdanova and **S.A. Pisarevsky** A Sm-Nd eclogite and U-Pb detrital zircon study of a probable Baltic HP-UHP metamorphic terrane in the Greenland Caledonides H. Brueckner, **E. Belousova**, L. Medaris, S. Johnston, **W. Griffin**, E. Hartz, S. Hemming and R. Bubbico Constraints on biogenic emplacement of crystalline calcium carbonate and dolomite **B. Colas, S.M. Clark** and **D.E. Jacob** Paleoproterozoic collisional structures in the Hudson Bay lithosphere constrained by multi-observable probabilistic inversion F. Darbyshire, **J.C. Afonso** and R. Porritt Supercontinent cyclicity: Relevant data, constraints, limitations and aspects requiring particular attention B. Eglington, D.A.D. Evans, S. Pehrsson and **Z.X. Li** The Capricorn Orogen Passive Source Array (COPA) in Western Australia **K. Gessner**, **H. Yuan**, R. Murdie, M.I. Dentith, S. Johnson and J. Brett REE chemistry of MORB and OIB explained by microchemical disequilibrium melting models **C. Grose** and **J. Afonso** Tasmania in Nuna: Witness to a ~1.4 Ga East Antarctica-Laurentia connection J. Halpin, J. Mulder and **N.R. Daczko** Extreme variability of deformation mechanisms at tiny scale in natural peridotite: the effect of phase distribution and mineral reactions **M.A. Kaczmarek**, **S. Reddy** and P. Vonlanthen Little and large: Implications for preservation of radiogenic-Pb in titanite. An example from the Albany-Fraser Orogen, Australia: Resolving process through Geochronology: New techniques, applications, and interpretations **C.L. Kirkland** Anomalous sulfur isotope signatures preserved in the Proterozoic rock record: insight into the link between fluid-driving tectonic processes and ore genesis at cratonic margins **C. LaFlamme**, **M.L. Fiorentini**, S. Johnson, B. Wing, **H. Jeon** and S. Occhipinti Using multiple sulfur isotope signatures to delineate terrane boundaries and investigate crustal formation mechanisms during the Paleoproterozoic **C. LaFlamme**, **M. Fiorentini**, B. Wing and **H. Jeon** First row transition metals in olivine - Petrogenetic tracers for the evolution of mantle-derived magmas M. Locmelis, R. Jr. Arevalo, I.S. Puchtel, S.J. Barnes and **M.L. Fiorentini** How Earth works 100 years after Wegener's continental drift theory and IGCP 648 **Z.X. Li**, D.A.D. Evans, S. Zhong and B. Eglington New Insight into the crustal structures of SE Australian continent from a combined study of ambient noise tomography and gravity modelling **C.X. Jiang**, **Y.J. Yang** and N. Rawlinson Petrologically-constrained thermo-chemical modelling of cratonic upper mantle consistent with elevation, geoid, surface heat flow, seismic surface waves and MT data A. Jones and **J. Afonso** **Invited**

AGU Fall Meeting, San Francisco, USA, 14-18 December 2015 *cont...*

Extreme variability of deformation mechanisms at tiny scale in natural peridotite: the effect of phase distribution and mineral reactions
M.A. Kaczmarek, **S.M. Reddy** and P. Vonlanthen

Morphological characteristics of detrital zircon grains from source to sink (Western Australia); Geochemistry of sediments and sediment recycling and implications for crust and mantle evolution over Earth history
V. Markwitz and **C.L. Kirkland**

Tracking CO_2 geosequestration using downhole gravity gradiometry, Otway Basin, Victoria, Australia
S. Matthews and **C. O'Neill**

The oxidation state of iron in chromite as a record of deep Earth processes
N.M. McGowan, **W.L. Griffin**, **N.J. Pearson**, **S.Y. O'Reilly**, **S.M. Clark**, J. Roque-Rosell, M.A. Marcus and **C.A. McCammon**

Multi-phase multi-component reactive flow in geodynamics
B. Oliveira, **J.C. Afonso** and S. Zlotnik

An early, transient, impact-driven tectonic regime in the Hadean
C. O'Neill, S. Marchi and **S. Zhang** **Invited**

Mapping sub-crustal reflectors in southwestern Spain
I. Palomeras, P. Ayarza, R. Carbonell, S. Ehsan, **J. Afonso** and J. Diaz Cusi

Mesoproterozoic - Tonian paleogeography: new insights
S.A. Pisarevsky

Why lithospheric extension separated the Aegean from Turkey
T. Ring, **K. Gessner**, S. Thomson and V. Markwitz

Os isotope evidence for a differentiated plume head reservoir for the Ontong Java Nui source
B. Schaefer, K. Hoernle, I. Parkinson, R. Golowin, M. Portnyagin, **S. Turner** and R. Werner

The formation of micro diamonds in dislocation creep controlled by the C:O:H ratio of NAMS
H. Sommer, K. Regenauer-Lieb, **D. Jacob** and B. Gasharova

Rare earth element partition coefficients during high-grade metamorphism: experiments, realities, and large datasets
R. Taylor, **C. Clark**, A. Kylander-Clark and B. Hacker

Thermophysical structure of the crust beneath the US Intermountain West from Multi-Observable Probabilistic Inversion
M.T. **Qashqai**, **J.C. Afonso**, **Y. Yang** and D. Schutt

Viscosity formulations and the effect of uncertain parameters
J. Wasiliev and **C. O'Neill**

Interactions among mid-ocean ridges, plumes and Large Igneous Provinces
J. Whittaker, **J. Afonso**, S. Masterton, D. Müller, P. Wessel, S. Williams and M. Seton **Invited**

Unraveling the unusual morphology of the Cretaceous Dirck Hartog extinct mid-ocean ridge
S. Watson, J. Whittaker, J. Halpin, S. Williams, L. Milan, **N. Daczko** and D. Wyman

Density effects of shallow structures on the crustal shear wavespeeds in surface wave tomography
G. Xing, M. Chen, F. Niu and **Y. Yang**

Unraveling overtone interferences in Love-wave phase velocity measurements by array-based, radon transform
Y. Yang and Y. Luo

Integrated *in situ* U-Pb age and Hf-O analyses of zircon from the Northern Yangtze Block: New insights into the Neoproterozoic Low-δ^{18}O Magmas in the South China Block
Y.N. Yang, **X.C. Wang**, Q.L. Li and X.H. Li

South China connected to north India in Gondwana: sedimentary basin and detrital provenance analyses
W. Yao, **Z.X. Li**, W.X. Li, X.H. Lia and J.H. Yang

Secular change in Archean crust formation recorded in Western Australia
H. Yuan

Broadband finite frequency ambient noise tomography
K. Zhao, **Y. Yang**, Y. Luo and J. Xie

A reduced basis approach for implementing thermodynamic phase-equilibria information in geophysical and geodynamic studies
S. Zlotnik, **J. Afonso** and P. Diez

Appendix 7: CCFS visitors

CCFS VISITORS 2015 (Excluding participants in conferences and workshops)

VISITOR	ORGANISATION	COUNTRY
Dr Chris Adams	Lower Hutt	New Zealand
Professor Yinshuang Ai	Inst. of Geology and Geophysics, Chinese Academy of Sciences, Beijing	China
Professor Jonathan Aitchison	University of Queensland, Brisbane	Australia
Dr Sarmad Ali	School of Earth & Environmental Sciences, University of Wollongong	Australia
Dr Bjarne Almqvist	Department of Earth Sciences (Geophysics), Uppsala University	Sweden
Professor Anne-Sylvie Andre-Mayer	Universite de Lorraine, Nancy	France
Associate Professor Paul Ashley	University of New England	Australia
Dr Lenka Baratoux	Laboratoire GET, University of Toulouse	France
Dr David Baratoux	Geosciences Environnement Toulouse, Centre National de la Recherche Scientifique (CNRS), University of Toulouse	France
Dr Charlotte Barry	Geological Survey of NSW	Australia
Ms Emily Bathgate	University of Technology, Sydney	Australia
Mr Trygvi Bech Arting	Geological Survey of Denmark and Greenland (GEUS)	Denmark
Dr Graham Begg	Minerals Targeting International	Australia
Ms Robin-Mary Bell	Geological Survey of Denmark and Greenland (GEUS)	Denmark
Dr Anne Briais	Geosciences Environnement Toulouse, Centre National de la Recherche Scientifique (CNRS), University of Toulouse	France
Dr Michael Bruce	Geological Survey of NSW	Australia
Mr Tim Chapman	School of Geosciences, University of Sydney	Australia
Mr Mathieu Chasse	Sorbonne Universites, Paris	France
Professor Qifu Chen	Inst. of Geology and Geophysics, Chinese Academy of Sciences, Beijing	China
Professor Ling Chen	Inst. of Geology and Geophysics, Chinese Academy of Sciences, Beijing	China
Professor Hanlin Chen	Zhejiang University, Hangzhou	China
Professor Geoff Clarke	The University of Sydney	Australia

VISITOR	ORGANISATION	COUNTRY
Professor Bill Collins	Newcastle University	Australia
Mr Rod Davis	VALE Exploration	Australia
Mr Benedikt Demmert	Friedrich-Alexander University, Erlangen-Nuremberg	Germany
Professor Pedro Díez	Universitat Politècnica de Catalunya, Barcelona	Spain
Ms María Laura Fernandez	Head of International Cooperation, National Agency for Research and Innovation (ANII)	Uruguay
Dr Joel Fitzherbert	Geological Survey of NSW	Australia
Professor Juan Manuel Garcia-Ruiz	University of Granada	Spain
Mr Chad Gardner	University of NSW	Australia
Dr Andrea Giuliani	University of Melbourne	Australia
Dr Bronislav Gongalskiy	Institute of Geology of Ore Deposits, Petrology, Mineralogy and Geochemistry, Russian Academy of Sciences (IGEM RAS), Moscow	Russia
Dr José María González-Jiménez	Universidad de Chile, Santiago	Chile
Dr Ian Graham	School of BEES, UNSW, Kensington	Australia
Dr John Greenfield	Geological Survey of NSW	Australia
Dr Jacqueline Halpin	University of Tasmania	Australia
Associate Professor Galen Halverson	McGill University, Montreal	Canada
Dr Hooshang Asadi Haroni	Isfahan University of Technology in Iran	Iran
Professor Yumei He	Inst. of Geology and Geophysics, Chinese Academy of Sciences, Beijing	China
Ms Zong-Ying Huang	Guangzhou Institute of Geochemistry, CAS	China
Professor Herbert Huppert	Department of Applied Mathematics and Theoretical Physics, University of Cambridge	UK
Ms Ping Ji	China Earthquake Administration	China
Ms Anne Johannesen	Geological Survey of Denmark and Greenland (GEUS)	Denmark
Dr Alan Kobussen	Principal Geologist, Rio Tinto Exploration	Australia
Professor Jochen Kolb	Geological Survey of Denmark and Greenland (GEUS)	Denmark
Professor Kurt Konhauser	University of Alberta	Canada
Dr Nadezda Krivolutskaya	Vernadsky Institute, Russian Academy of Sciences (GEOKHI RAS), Moscow	Russia
Professor Nikolay Kuznetsov	Geological Institute, Russian Academy of Science, Moscow	Russia
Dr Zhen Li	China University of Petroleum	China
Mr Shilin Li	Peking University	China
Dr Jianjiao Li	Research Inst. of Petroleum Exploration & Development, SINOPEC, Beijing	China
Dr Jingchang Li	Research Inst. of Petroleum Exploration & Development, SINOPEC, Beijing	China
Professor Xian-Hua Li	China Academy of Sciences, Beijing	China
Dr Bo Li	University of Wollongong	Australia
Adjunct Professor Robert Loucks	Geoscience Research Consultant	USA
Mr Xiang Lu	China University of Geosciences, Wuhan	China
Professor Yinhe Luo	China University of Geosciences, Wuhan	China
Ryan Manton	University of Wollongong	Australia
Dr Helen Maynard-Casely	Australian Nuclear Science and Technology Organisation	Australia
Dr David McPhail	Imperial College London	UK
Dr Luke Milan	University of New England, Armidale	Australia
Dr Marilena Moroni	University of Milano, Italy	Italy

VISITOR	ORGANISATION	COUNTRY
Mr Antoine Neaud	University of Toulouse	France
Professor Allen Nutman	University of Wollongong	Australia
Professor Nick Rawlinson	University of Aberdeen	UK
Professor Mark Reagan	University of Iowa	USA
Professor Klaus Regenauer-Lieb	University of New South Wales	Australia
Dr Michael Roach	Earth Sciences, University of Tasmania	Australia
Dr Tatiana V. Romanyuk	Schmidt Institute of Physics of the Earth, Russian Academy of Science, Moscow	Russia
Ms Nanna Rosing-Schow	Geological Survey of Denmark and Greenland (GEUS)	Denmark
Dr Gary Scott	UC Berkeley, San Francisco	USA
Dr Rodolfo Silveira	President, Technological Laboratory of Uruguay (LATU), and Adviser, Universidad Tecnológica del Uruguay (UTEC)	Uruguay
Dr Zdislav Spetsius	Geology of Diamond Deposits NIGP, Alrosa Co Ltd, Yakutia	Russia
Dr Jeff Steadman	CODES, University of Tasmania	Australia
Mr Luke Steller	School of BEES, UNSW, Kensington	Australia
Dr Xiang Sun	China University of Geosciences, Beijing	China
Dr Dongsheng Sun	Research Inst. of Petroleum Exploration & Development, SINOPEC, Beijing	China
Mr Michael Tetley	EarthByte, The University of Sydney	Australia
Dr Andy Tomkins	Monash University	Australia
Dr Mark van Zuilen	Institute de Physique du Globe de Paris, Paris	France
Professor Thomas Vogt	Department of Chemistry and Biochemistry, University of South Carolina	USA
Dr Kuo-Lung Wang	Institute of Earth Sciences, Academia Sinica, Taipei	Taiwan
Professor Qinyan Wang	China University of Geosciences, Wuhan	China
Associate Professor Changming Wang	China University of Geosciences, Beijing	China
Dr Simon Williams	The University of Sydney	Australia
Dr Boswell Wing	McGill University, Montreal	Canada
Dr Stephan E. Wolf	Institute for Glass and Ceramics, Erlangen	Germany
Dr Shiqiang Wu	Research Inst. of Petroleum Exploration & Development, SINOPEC, Beijing	China
Mr Jiang Wu	Research Inst. of Petroleum Exploration & Development, SINOPEC, Beijing	China
Dr Jia Wu	University of Petroleum	China
Professor Yixian Xu	China University of Geosciences, Wuhan	China
Professor Yigang Xu	China Academy of Sciences, Guangzhou	China
Dr Tong Yang	China University of Geosciences, Wuhan	China
Professor Jin-Hui Yang	China Academy of Sciences, Beijing	China
Dr Sabin Zahirovic	EarthByte Group, School of Geosciences, The University of Sydney	Australia
Associate Professor Georg Zellmer	Massey University	New Zealand
Dr Zhongpei Zhang	Research Inst. of Petroleum Exploration & Development, SINOPEC, Beijing	China
Dr Zhili Zhang	Research Inst. of Petroleum Exploration & Development, SINOPEC, Beijing	China
Professor Lifei Zhang	Peking University	China
Professor Liang Zhao	Inst. of Geology and Geophysics, Chinese Academy of Sciences, Beijing	China
Professor Tianyu Zheng	Inst. of Geology and Geophysics, Chinese Academy of Sciences, Beijing	China

Appendix 8: Research funding

GRANTS AND OTHER INCOME FOR 2015

Investigators	2015 Funding Source	Project Title	Amount
O'Reilly	ARC Centre of Excellence	Core to Crust Fluid Systems	$1,969,500
Wilde	ARC CoE (Curtin contribution)	Core to Crust Fluid Systems	$328,368
GSWA	ARC CoE (GSWA)	Core to Crust Fluid Systems	$150,000
O'Reilly	ARC CoE (MQ contribution)	Core to Crust Fluid Systems	$440,000
O'Reilly	ARC CoE (MQ FSE contribution)	Core to Crust Fluid Systems	$110,000
McCuaig	ARC CoE (UWA contribution)	Core to Crust Fluid Systems	$320,000
Yang, Rawlinson	ARC Discovery Project (DP120103673)	Down under down under: using multi-scale seismic tomography to image beneath Australia's Great Artesian Basin	$85,458
Rosenbaum, Pisarevsky, Fielding, Speranza	ARC Discovery Project (DP130100130)	Unravelling the geodynamics of eastern Australia during the Permian: the link between plate boundary bending and basin formation	$45,626
Moresi, Betts, Whittaker, Miller	ARC Discovery Project (DP150102887)	The global consequences of subduction zone congestion	$150,000
Handley, Turner, Reagan, Barclay	ARC Discovery Project (DP150100328)	Timescales of mixing and volatile transfer leading to volcanic eruptions	$127,239
Fitzsimons, Holness, Clark	ARC Discovery Project (DP150102773)	Migmatites, charnockites and crustal fluid flux during orogenesis	$65,000
Li	ARC Australian Laureate Fellowship (FL150100133)	How the Earth works - toward building a new tectonic paradigm	$295,199
Alard	ARC Future Fellowship (FT150100115)	Earth's origin and evolution: a sulphurous approach	$100,620
Belousova	ARC Future Fellowship (FT110100685)	Dating down under: resolving Earth's crust - mantle relationships	$100,801
Fiorentini	ARC Future Fellowship (FT110100241)	From core to ore: emplacement dynamics of deep-seated nickel sulphide systems	$94,847
Handley	ARC Future Fellowship (FT120100440)	The timescales of Earth-system processes: extending the frontiers of uranium-series research	$173,164
Jacob	ARC Future Fellowship (FT120100462)	A new approach to quantitative interpretation of paleoclimate archives	$232,676
Piazolo	ARC Future Fellowship (FT110100070)	Flow characteristics of lower crustal rocks: developing a toolbox to improve geodynamic models	$114,844
Wacey	ARC Future Fellowship (FT140100321)	New insights into the origin and evolution of life on Earth	$191,766
Wang	ARC Future Fellowship (FT140100826)	Roles of deep-Earth fluid cycling in the generation of intra-continental magmatism	$196,832

Investigators	2015 Funding Source	Project Title	Amount
Yang	ARC Future Fellowship (FT130101220)	How the Earth moves: Developing a novel seismological approach to map the small-scale dynamics of the upper mantle	$194,644
Selway	ARC Future Fellowship (FT150100541)	Measuring mantle hydrogen to map ore fluids and model plate tectonics	$75,294
Giuliani	ARC DECRA (DE150100510)	A new approach to revealing melting processes in the hidden deep Earth	$126,222
Giuliani	MQ	Project supliment	$100,000
Arculus, Rohling, Roberts, Exon, Yeats, O'Reilly, George, Muller, Aitchison, Webster, Coffin, Vasconcelos, Welsh, McCuaig et al.	ARC LIEF (LE140100047)	Australian membership of the International Ocean Discovery Program	$1,800,000
Kemp, McCulloch, Fiorentini, McCuaig, Rate, Clark, Rasmussen, Evans, Reddy, Bland, Raimondo, Pearson, Belousova, Jacob, Runatto, Spandler, Barnes	ARC LIEF (LE150100013)	Expanding the frontiers of mass spectrometry: a high resolution laser ablation multiple streaming facility	$860,000
Pearson et al.	ARC LIEF (LE150100013) MQ contribution	Expanding the frontiers of mass spectrometry: a high resolution laser ablation multiple streaming facility	$40,000
Li, Tohver, Roberts, Rosenbaum, O'Neill, Pisarevsky, Clark, Elders, Bland, Wilde	ARC LIEF (LE150100065)	A fully automated, fully shielded palaeomagnetic system	$560,000
Li, Tohver, Roberts, Rosenbaum, O'Neill, Pisarevsky, Clark, Elders, Bland, Wilde	ARC LIEF (LE150100065) CU contribution	A fully automated, fully shielded palaeomagnetic system	$550,000
Li, Tohver, Roberts, Rosenbaum, O'Neill, Pisarevsky, Clark, Elders, Bland, Wilde	ARC LIEF (LE150100065) MQ contribution	A fully automated, fully shielded palaeomagnetic system	$20,000
McCuaig, Hobbs, Liu, Gorczyk, Cawood, Connolly, Gerya, Lester, Gessner	ARC Linkage Project (LP100200785)	Multiscale dynamics of ore body formation	$24,138
Tkalcic, Kennett, Spaggiari, Gessner	ARC Linkage Project (LP130100413)	Craton modification and growth: the east Albany-Fraser Orogen in three-dimensions	$100,000
Rasmussen, Dunkley, Muhling, Johnson, Thorne, Korhonen, Kirkland, Wingate	ARC Linkage Project (LP130100922)	Chronostratigraphic and tectonothermal history of the northern Capricorn Orogen: constructing a geological framework for understanding mineral systems	$170,000
Jessell, Holden, Baddeley, Kovesi, Ailleres, Wedge, Lindsay, Gessner, Hronsky	ARC Linkage Project (LP140100267)	Reducing 3D geological uncertainty via Improved data interpretation methods	$120,000
Aitken, Dentith, Lindsay, McCuaig	Geological Survey of Western Australia	Second generation regional targeting products	$245,833

Investigators	2015 Funding Source	Project Title	Amount
Fiorentini	Geological Survey of Western Australia	Mapping sulfur sources in selected Precambrian terranes of Western Australia to enhance predictive targeting for gold and base metal mineralization	$15,000
McCuaig, Greenwood, McCulloch	CSIRO Flagship Collaboration Fund	Mineral systems flagship cluster	$108,033
Hough, McCuaig, Reddy, Clark, Fiorentini, Gray, Miller	MERIWA	Distal footprints of giant ore systems	$850,000
Hough, McCuaig, Reddy, Clark, Fiorentini, Gray, Miller	SIEF	Distal footprints of giant ore systems	$345,380
Hough, Reddy, McCuaig	SIEF RP	The distal footprints of giant ore systems: UNCOVER Australia	$853,000
Barnes, Fiorentini	MRIWA M459	Magmatic sulfide mineral potential in the East Kimberley	$61,320
Ord, Gorczyk, Hobbs, Micklethwaite	MERIWA M424	Multiscale dynamics of hydrothermal mineral systems	$195,800
Caruso	MRIWA scholarship	CCFS-related PhD project	$30,000
C. Adams	MRIWA scholarship	CCFS-related PhD project	$30,000
O'Reilly	NCRIS AuScope	A4.45; Macquarie University Project - Earth Composition and Evolution	$211,000
O'Reilly	NCRIS AuScope MQ contribution	A4.45; Macquarie University Project - Earth Composition and Evolution	$50,000
O'Reilly, Griffin, Pearson, Belousova, Jacob, Piazolo, Clark, Daczko, Foley, George, Rushmer, Turner, Dadd, Schaefer, Handley, Downes, Lang, Brock	MQSIS	CL Monochromator for scanning electron microscopy	$150,000
Clark, Afonso, Jacob, Pearson, Rushmer, Foley, Griffin, O'Reilly, Turner	MQSIS	Core to crust experiments: Establishment of a high-pressure, high-temperature Diamond Anvil Cell facility	$64,877
Afonso	MQRIBG	Cluster computing for large-scale geophysical simulations: Towards an integrated multidisciplinary framework	$98,500
Withford, Downes, Twamley, O'Neill, Cartmill, McMullan, Inglis, Connor, Tristant, Appleyard, Chung, Clark, Foley, Atkin, Jackson, O'Reilly, Pearson, Griffin	MQSIS	3D printing facility	$500,000
Clark, Afonso, Turner, O'Neill, Pearson, Piazolo, Rushmer, Foley, O'Reilly	MQRIBG	*In-situ* studies of materials under deep Earth conditions: building on synergies between current Raman and Diamond Anvil Cell facilities	$61,405
McGowan	International Synchrotron Access Program	International Synchrotron Access Program	$6,400
Gardner	MQPGRF	What can asymmetry tell us? Investigation of asymmetric versus symmetric pinch and swell structures in nature and simulation	$4,623

Investigators	2015 Funding Source	Project Title	Amount
Stuart	MQPGRF	Flow characteristics of lower crustal rocks: characterising melt migration in the lower crust	$3,785
Tretiakova	MQPGRF	The nature, extent and age of the lower crust and underlying subcontinental lithospheric mantle (SCLM) beneath the Siberian Craton (Russia)	$5,000
Matthews	MQPGRF	Tracking CO_2 sequestration using gravity gradiometry	$4,811
Tork Qashqai	MQPGRF	Inversion of multiple geophysical data for composition and thermal structure of Earth's upper mantle	$4,857
Peters	MQPGRF	Biomarkers and fluid inclusions of early Earth using samples from Australia	$5,000
Oliveira	La Caixa Scholarship	Beca para cursar estudios de posgrado en la zona Asia-Pacífico	$65,000
Dering, Fiorentini	SEG Grant	Segmentation and organisation of mafic magmas in arc settings	$4,000
McGowan	AGU Student Travel Grant	AGU General Fall Meeting	$1,000 USD
Dadd	Open Fund Project of the State Key Lab of Marine Geology, Tongji University, China	Understanding magmatic processes in the South China Sea region as recorded in deep sea sediments	$100,000 RMB
Van Kranendonk, Keleman	Alfred P Sloan Foundation	Integrative field studies for the deep carbon observatory	$46,250
Clark, Colas, Darwish, Fernandez-Martinez, Kalkan, Kimpton, Struder	Braggs Institute, ANSTO	A determination of the hydrogen bonding network in amorphous calcium carbonate	$16,700
Jacob, Clark, Colas Wood	Braggs Institute, ANSTO	Non-classical nucleation pathways in $CaCO_3$	$28,560
Clark, Colas, Piltz,	Braggs Institute, ANSTO	Determining the position of water molecules in olivine	$34,500
Clark, Amulele, Mole	Braggs Institute, ANSTO, award 5043, 4478	Determination of proton conduction in olivine	$59,100
Clark, Colas, Piltz	Braggs Institute, ANSTO	Refining the position of water molecules in olivine	$33,500
Piazolo, Salvemini, Fiorentini	Neutron Proposal, Bragg Institute	Textural analysis of Martian meteorites: Deciphering the formation and evolution of the Martian crust	$55,200
Rushmer	ANSTO	ANSTO/MQ funding for a 5 year academic position	$291,492
Dadd	ANZIC Post-cruise Funding	Analysis of volcanic ash - IODP Exp 349	$40,000
Huang, Dadd, Pearson, Gréau, Griffin, O'Reilly	ANZIC Special Analytical Funding	Mg-isotope composition of altered oceanic crust	$20,000
Dentith, Fiorentini	ASEG Research Foundation	Understanding of the petrophysical properties of altered rocks: Implications for geophysical exploration	$23,000
Fiorentini, Baumgartner, Micklethwaite, Barnes, Baratoux, Thebaud, Sener	Australian Synchrothron Proposal 8538	The distribution of Ni, Cu and Pt in the Martian meteorites: Constraints on the metal budget of source magmas and metal fractionation processes	$98,000
McCuaig, Jara Barra	Barrick Gold	Gold pathways: evolution of the lithospheric to crustal architecture of the El Indio Belt, Chile-Argentina	$55,445
Bevitt, McMahon, Jacob, Garbe	Bragg Institute/ANSTO	Imaging giant clam shell growth	$14,000

Investigators	2015 Funding Source	Project Title	Amount
Martin	Fay-Gale Fellowship UWA	Staff grant	$7,800
Lampinen	Hugo Dummett Mineral Discovery Fund	Society of Economic Geologists Foundation, Inc.	$4,202
Fiorentini, Loucks, McCuaig	Rio Tinto	Enhanced predictive capability for targeting high quality magmatic hydrothermal copper, gold and molybdenum deposits	$106,110
George, Wood, O'Brien, Madin, Armand, Bishop, Armbrecht, Brock, Daczko, Dadd, Goodwin, Grech, Hesse, Irvine, Jacob, Kennedy, Kosnik, Loehr, Madin, Ostrowski, Paulsen, Neil, Tetu, Williamson	Macquarie Research Centre	Oceans at Macquarie	$29,791
Baumgartner, Caporali, Luzin, Salvemini, Piazolo, Fiorentini	Neutron Proposal 4418	Textural analysis of Martian meteorites: Deciphering the formation and evolution of the Martian crust	$55,200
Yang, Lu	NSFC	Genesis of comb quartz layers: case studies from porphyry Cu deposits at Qulong, Tibet and Now Chun, Iran	$50,000
Lampinen, Occhipinti	Research Grant	ASEG Research Foundation	$8,200
Lampinen	TerraSpec Student in Mining Instrument Programme	Sponsored equipment	*$60,000 USD
Rushmer, Zellmer	National Geographic Society	Dynamics of magma ascent beneath New Zealand's subduction zone volcanoes: implications for hazard mitigation strategies	$24,292
Griffin, O'Reilly, Pearson, Belousova	MQ Enterprise Partnership Pilot Research Grant (Minerals Targeting International Pty Ltd)	Lithospheric architecture mapping in Phanerozoic orogens	$60,000
Pisareskiy	UWA-UQ Bilateral Research Collaboration Award	Orogenic bending and the sedimentary record	$5,540
O'Reilly	DVCR Discretionary Fund	EOI for CoE 2017 round	$12,500
Rushmer, Turner, Foley, Clark	DVCR Discretionary Fund	Support for the MOU between Maquarie University and GeoForschungsZentrum for the development of a joint high-pressure research program	$64,000
Li, Evans, Zhong, Eglington	UNESCO-IUGS IGCP Project	IGCP project #648: Supercontinent cycles and global geodynamics	$10,000 USD
Yao	China Geological Survey	Basin analysis of Ediacaran-Silurian strata on the western Yangtze margin	$21,453
O'Reilly	MQ Distinguished Professor Grant	Distinguished Professor grant	$12,000
Griffin	MQ Distinguished Professor Grant	Distinguished Professor grant	$12,000
Clark	Research Development Grant (MQ)	Imaging a subduction zone: Understanding the sources of earthquakes and volcanoes at convergent plate boundaries	$12,099

Investigators	2015 Funding Source	Project Title	Amount
Kirkland	Ministry of Mineral Resources (Greenland)	Geochronology for the Greenland Ministry of Mineral Resources	$56,138
Kirkland	Department of Mines and Petroleum	Crustal evolution project Geological Survey of Western Australia	$44,173
O'Neill	CO_2 CRC Student Scholarship	CO_2 CRC	$30,000
CCFS Postgraduates	MQ, CU, UWA Scholarships	Scholarships	$2,375,090
O'Reilly	Access MQ	Core to Crust Fluid Systems	$128,090
O'Reilly	GLITTER software	Core to Crust Fluid Systems	$73,537
O'Reilly	Interest	Post Award and SLF interest	$73,537

GRANTS AND OTHER INDICATIVE INCOME FOR 2016

Investigators	2016 Funding Source	Project Title	Amount
O'Reilly	ARC Centre of Excellence	Core to Crust Fluid Systems	$2,020,500
Wilde	ARC CoE (Curtin contribution)	Core to Crust Fluid Systems	$280,000
GSWA	ARC CoE (GSWA)	Core to Crust Fluid Systems	$150,000
O'Reilly	ARC CoE (MQ contribution)	Core to Crust Fluid Systems	$550,000
O'Reilly	ARC CoE (MQ EPS contribution)	Core to Crust Fluid Systems	$110,000
McCuaig	ARC CoE (UWA contribution)	Core to Crust Fluid Systems	$320,000
Putnis, Raimondo, Daczko	ARC Discovery Project (DP160103449)	Just add water: a recipe for the deformation of continental interiors	$181,006
Moresi, Betts, Whittaker, Miller	ARC Discovery Project (DP150102887)	The global consequences of subduction zone congestion	$172,000
Handley, Turner, Reagan, Barclay	ARC Discovery Project (DP150100328)	Timescales of mixing and volatile transfer leading to volcanic eruptions	$105,500
Fitzsimons, Holness, Clark	ARC Discovery Project (DP150102773)	Migmatites, charnockites and crustal fluid flux during orogenesis	$52,700
Jacob/Eggins	ARC Discovery Project (DP160102081)	Mechanisms of proxy uptake in biominerals	$100,000
Hand, Clark, Hasterok, Rushmer, Reddy, Hacker	ARC Discovery Project (DP160104637)	Rehydration of the lower crust, fluid sources and geophysical expression	$115,000
Clark, Afonso, Jones	ARC Discovery Project (DP160103502)	To develop a geophysically relevant proton conduction model for the Earth's upper mantle	$93,475
Li	ARC Australian Laureate Fellowship (FL150100133)	How the Earth works - toward building a new tectonic paradigm	$593,891
Handley	ARC Future Fellowship (FT120100440)	The timescales of Earth-system processes: extending the frontiers of uranium-series research	$72,878
Jacob	ARC Future Fellowship (FT120100462)	A new approach to quantitative interpretation of paleoclimate archives	$102,800
Wacey	ARC Future Fellowship (FT110100070)	New insights into the origin and evolution of life on Earth	$191,956

Investigators	2016 Funding Source	Project Title	Amount
Wang	ARC Future Fellowship (FT140100321)	Roles of deep-Earth fluid cycling in the generation of intra-continental magmatism	$196,832
Yang	ARC Future Fellowship (FT140100826)	How the Earth moves: Developing a novel seismological approach to map the small-scale dynamics of the upper mantle	$179,077
Alard	ARC Future Fellowship (FT150100115)	Earth's origin and evolution: a sulphurous approach	$199,240
Selway	ARC Future Fellowship (FT150100541)	Measuring mantle hydrogen to map ore fluids and model plate tectonics	$163,088
Arculus, Cohen, Gallagher, Vasconcelos, Elders, Foden, Coffin, Nebel, McGregor, Clennell, Sloss, Heap, Webster, Kemp, George	ARC LIEF (LE160100067)	Australian membership of the International Ocean Discovery Program	$2,000,000
Foley, Mavrogenes, Putnis, Brugger, Clark, Simon, O'Neil, Cruden, Evans	ARC LIEF (LE160100103)	Australian virtual experimental laboratory: a multimode geoscience facility	$547,000
Kennedy, Sorrell, Haberlah, Dewhurst, Turner, Gore, O'Reilly, van Kranendonk, Foden, Nelson, Haghighi, Le-Clech, Ward, Koshy, Sherwood	ARC LIEF (LE160100155)	NanoMin: quantitative mineral mapping of nonoscale processes	$648,000
Tkalcic, Kennett, Spaggiari, Gessner	ARC Linkage Project (LP130100413)	Craton modification and growth: the east Albany-Fraser Orogen in three-dimensions	$50,000
Rasmussen, Dunkley, Muhling, Johnson, Thorne, Korhonen, Kirkland, Wingate	ARC Linkage Project (LP130100922)	Chronostratigraphic and tectonothermal history of the northern Capricorn Orogen: constructing a geological framework for understanding mineral systems	$85,000
Jessell, Holden, Baddeley, Kovesi, Ailleres, Wedge, Lindsay, Gessner, Hronsky	ARC Linkage Project (LP140100267)	Reducing 3D geological uncertainty via Improved data interpretation methods	$100,000
Giuliani	ARC DECRA (DE150100510)	A new approach to revealing melting processes in the hidden deep Earth	$124,000
Giuliani	Marie Curie Grant	Kimberlite new approach	€177,598
Aitken, Dentith, Lindsay, McCuait	Geological Survey of Western Australia	Second generation regional targeting products	$346,146
Hough, McCuaig, Reddy, Clark, Fiorentini, Gray, Miller	MERIWA	Distal footprints of giant ore systems	$850,000
Hough, McCuaig, Reddy, Clark, Fiorentini, Gray, Miller	SIEF	Distal footprints of giant ore systems	$346,146
Hough, Reddy, McCuaig	SIEF RP	The distal footprints of giant ore systems: UNCOVER Australia	$653,000
Fiorentini et al.	MERIWA M436	Distal footprints of giant ore systems: Capricorn WA case study	$451,186
Kirkland, Clark, Kiddie, Tyler, Spaggiari, Smithies, Wingate	MRIWA M470	Mineral systems on the margin of cratons: Albany-Fraser Orogen/ Eucla Basement case study	$254,429
Caruso	MRIWA Scholarship	CCFS-related PhD project	$30,000
C. Adams	MRIWA Scholarship	CCFS-related PhD project	$30,000
Choi	MRIWA Scholarship	CCFS-related PhD project	$30,000

Investigators	2016 Funding Source	Project Title	Amount
Petrella	MRIWA Scholarship	CCFS-related PhD project	$29,000
Stirling	MRIWA Scholarship	CCFS-related Masters project	$29,000
O'Reilly	NCRIs AuScope	AuScope Project Plan 3.53	$190,000
O'Reilly	NCRIS AuScope MQ contribution	A4.45; Macquarie University Project - Earth Composition and Evolution	$50,000
O'Reilly	RAAP	AuScope Earth Composition and Evolution	$350,000
Piazolo	MQSIS	Precision lapping machine	$147,800
Jacob et al.	MQRIBG	A state-of-the-art solid material preparation system for microbeam applications	$46,591
Mildren, Clark, Downes, Williams, Heimlich, Esselle	MQRIBG	UV direct-write workstation for processing materials with sub-micron resolution	$96,146
Pearson	MQRIBG	Probe for EPMA software	$61,405
Kirkland	Ministry of Mineral Resources (Greenland)	Geochronology for the Greenland Ministry of Mineral Resources	$18,713
Kirkland	Department of Mines and Petroleum	Crustal evolution project Geological Survey of Western Australia	$44,173
Oliveira	La Caixa Scholarship	Beca para cursar estudios de posgrado en la zona Asia-Pacífico	$65,000
Dadd	ANZIC Post-cruise Funding	Analysis of volcanic ash - IODP Exp 349	$40,000
McCuaig et al.	Barrick Gold	The role of whole-lithosphere architecture on the genesis of giant gold systems in the El-Indio region, Chile-Argentina	$198,470
Piazolo, Schaefer, Turner	Bragg Institute/ANSTO	Hydration of the early solar system	$75,000
Yang, Lu	NSFC	Genesis of comb quartz layers: case studies from porphyry Cu deposits at Qulong, Tibet and Now Chun, Iran	$50,000
Lampinen	TerraSpec Student in Mining Instrument Programme	Sponsored equipment	$60,000 USD
Griffin, O'Reilly, Pearson, Belousova	MQ Enterprise Partnership Pilot Research Grant (Minerals Targeting International Pty Ltd)	Lithospheric architecture mapping in Phanerozoic orogens	$60,000
Li, Evans, Zhong, Eglington	UNESCO-IUGS IGCP Project	IGCP project #648: Supercontinent cycles and global geodynamics	$10,000 USD
O'Reilly	MQ Distinguished Professor	Distinguished Professor grant	$12,000
Griffin	MQ Distinguished Professor	Distinguished Professor grant	$12,000
C O'Neill	CO_2 CRC Student Scholarship	CO_2 CRC	$30,000
Yao	China Geological Survey	Basin analysis of Ediacaran-Silurian strata on the western Yangtze margin	$21,453
Colas	ANSTO Scholarship	Scholarship	$24,653

Appendix 9: Standard performance indicators

All values maximised at double target

Area	Category	Code	Indicator		Value
RESEARCH	Number & quality of outputs	R1	Research outputs	Actual	174
				Target	40
		R2(a)	Journals with Impact Factor >2.5	Actual	91%
				Target	70%
		R2(b)	Journals with impact Factor >3 Note: (11%>6)	Actual	81%
				Target	50%
		R2(c)	Journals with specific target audiences	Actual	13%
				Target	20%
		R2(d)	Book chapters / international conference proceedings	Actual	2%
				Target	10%
		R3(a)	Number of presentations / talks / papers / lectures given at major international meetings	Actual	213
				Target	40
		R3(b)	Number of invited or keynotes given at major international meetings	Actual	23
				Target	10
		R4	Number & nature of commentaries on Centre's achievements in general/specialist publications	Actual	32
				Target	8
		R5	Citation data for publications: at least 4 CI's in top 200 Geoscientists	Actual	4
				Target	4
	Research training and professional education	R6	Number of attended professional training courses for staff and postgraduate students	Actual	15
				Target	10
		R7	Number of Centre attendees at all professional training courses	Actual	68
				Target	20
		R8	Number of new postgraduates working on core Centre research, supervised by CoE staff (PhD, MRes)	Actual	24
				Target	8
		R9	Number of new postdoctoral researchers recruited to the CoE working on core Centre research	Actual	6
				Target	4
		R10	Number of new Honours/MRES students working on core Centre research & supervised by CoE staff	Actual	8
				Target	6
		R11(a)	Number of postgraduate completions working on core Centre research and supervised by CoE staff	Actual	18
				Target	6
		R11(b)	Postgraduate completion times: students working on core CoE research, supervised by Centre staff	Actual	3.5
				Target	3.5
		R12	Number of Early Career Researchers (within 5 years of completing PhD) working on core CoE research	Actual	11
				Target	6
		R13	Number of students mentored	Actual	100
				Target	24
		R14	Number of mentoring programs	Actual	4
				Target	3
	Build int. national and regional links/networks	R15	Number of international visitors and visiting fellows	Actual	71
				Target	20
		R16	Number of national and international workshops held / organised by Centre	Actual	11
				Target	3
		R17	Number of visits to overseas laboratories and facilities	Actual	44
				Target	20
		R18	Examples of relevant interdisciplinary research supported by the Centre	Actual	100%
				Target	>50%

RESEARCH	Build end-user links	R19	*Number of government, industry & business community briefings*	*Actual*	7
				Target	6
		R20	*Number and nature of public awareness programs*	*Actual*	6
				Target	5
		R21	*Currency of information on the Centre's website*	*Actual*	6
				Target	4
		R22	*Number of website hits*	*Actual*	13,929
				Target	10,000
		R23	*Number of public talks given by centre staff*	*Actual*	7
				Target	6

ORG SUPPORT	Generate cash & in-kind contributions from partners & other sources & build collab. & infrastrucutre support	O1	*Annual new and existing cash contributions from collaborating organisations*	*Actual*	2,375,090
				Target	1,790,000
		O2	*Annual in-kind contributions from collaborating organisations*	*Actual*	13,100,455
				Target	12,418,100
		O3	*Annual cash contributions from partner organisations*	*Actual*	150,000
				Target	150,000
		O4	*Annual in-kind contributions from partner organisations*	*Actual*	1,881,507
				Target	1,229,300
		O5	*Other research income secured by Centre staff*	*Actual*	11,721,227
				Target	140,000
		O6	*Number of new organisations collaborating with, or involved in, the Centre*	*Actual*	16
				Target	6
		O7	*Level and quality of infrastructure provided to the Centre*	Documented *pp. 83-92*	

GOVERNANCE	Intersect the right set of expertise to guide the Centre	G1	*Breadth, balance and experience of the members of the Advisory Board*	The Advisory Board includes senior representatives from industry and other end users such as Geoscience Australia (documented p. 9), and was endorsed by the Mid-term Review Panel.
		G2	*Frequency, attendance and value added by Advisory Committee meetings*	Two very productive Advisory Board meetings were held in March and October 2015. Attendance at the meetings was over 95%. Frequency of Board meetings exceeded target. Board input has been invaluable, including providing a different perspective of Centre activities, and has been very engaged in workshopping key aspects of Centre business and in realigning the CCFS Vision.
		G3	*Vision and usefulness of the Centre strategic plan*	Strategic plan was reviewed mid 2014 and endorsed by the CCFS Board and executive.
		G4	*Adequacy of the Centre's performance measure targets*	Centre's performance measure targets are discussed with the board annually. CCFS has consistently performed well against the current measures. As a result of feedback and reassessment post review, they continue to be revised on a regular basis.
		G5	*Effectiveness of the Centre in bringing researchers together to form an interactive and effective research team*	Jointly authored presentations and publications as well as co-supervised postgraduates (see *Appendices 5 and p. 76*)
		G6	*Capacity building of the Centre through scale and outcomes*	Recruitment of staff: 12 (see *pp. 10-13*) Recruitment of postgraduate students: 24 (see *pp. 76-82*) International Linkages: 71 (see *pp. 98-101*)

BENEFIT	Contribute to the national research agenda; expand the national capability in Earth Science	N1	*Industry Seminars*	*Actual*	4
				Target	4
			Number of industry / end-user collaborations		14
		N2	*Postgraduate units established by end year 3*	*Actual*	6
				Target	2
			Number of honours and Postgraduate students		100

CCFS KPI	Outcomes	C1	*Linkage of geochemical / petrologic / geological data with geophysical datasets / modelling* *2014 - Convene international conference on integration of geophysics / geology*	*Actual*	Complete
				Target	Complete
		C2	*Technology & method development related to NCRIS infrastructure* *2013 -1st results submitted for publication / conference presentation*	*Actual*	Complete
				Target	Complete
	Training	C3	*Establishment of formal postgraduate units & training within host and collaborating university frameworks*	*Actual*	Complete
				Target	Complete
	End-user	C4	*Establishment of linkages and collaborative projects with end-users relevant to external core business of the Centre* *2013 - proceed with projects*	*Actual*	Complete
				Target	Complete

Appendix 10: CCFS postgraduate opportunities

POSTGRADUATE OPPORTUNITIES

CCFS has a flourishing postgraduate research environment with postgraduate students from many countries (currently including France, Germany, China, Russia, USA, Canada and Australia). Scholarships funding tuition fees and a living allowance are available for students with an excellent academic record or equivalent experience.
These include:

- **Australian Postgraduate Awards (APA):** available for Commonwealth citizens to cover tuition fees and living allowance, with a closing date in late October annually at all universities.
- **International Postgraduate Research Scholarships (E-IPRS Endeavour Scholarships):** available to overseas students to cover tuition fees with a closing date in late August annually (http://www.innovation.gov.au/InternationalEducation/EndeavourAwards/Pages/default.aspx).
- **Macquarie University Research Excellence Scholarship (MQRES) scholarships:** available for Australian citizens and international students who wish to undertake a postgraduate program in a Centre of Excellence at Macquarie University (e.g. CCFS/GEMOC). These include cotutelle programs with international universities (http://www.mq.edu.au/research/phd-and-research-degrees/explore-research-degrees/cotutelle-and-joint-phd).
- **UWA Scholarship for International Research Fees (SIRF)**: available to eligible overseas candidates for higher degrees by research (HDR) at The University of Western Australia (http://spe.publishing.uwa.edu.au/latest/scholarships/postgraduate/sirf)
- **China Scholarship Council - Post-graduate Study Abroad Program** is a national scholarship program financing outstanding Chinese students (Chinese citizens) to study at top universities around the world. Curtin, Macquarie and UWA are partner universities in this program (http://www.csc.edu.cn/).

CCFS also provides research funding through competitive internal schemes; CCFS and externally funded projects provide further resources to support postgraduate research projects; and some CCFS support is available for approved postgraduate research support.

Postgraduate projects are tailored to your expertise and interests within the framework of CCFS research goals. CCFS carries out interdisciplinary research across the boundaries of petrology, geochemistry, tectonics, metallogenesis, geodynamics and geophysics to explore the nature and evolution of the Earth and global geodynamics. Current funded projects are based in Australia, Antarctica, Canada, China, Taiwan, Italy, France, Spain, Siberia, Norway, North America, South America, Africa, Kerguelen Islands, Greenland and other locations globally (see the map on *p. 19* of this Report).

CCFS postgraduate programs have opportunities through access to our outstanding analytical facilities (see *Technology Development* section) with currently unique technologies and instrumentation configurations to tackle exciting large-scale problems in the Geosciences.

Examples of broad PhD project areas include (but are not limited to):

- Lithosphere structure and geochemistry: mantle provinciality and tectonism
- Granitoid and mineralised provinces along western Pacific convergent margins
- Fluid-vapour transfer of elements in the crust and mantle
- Heat production and evolution of the crust: crust-mantle interaction
- Geophysical applications to lithosphere studies
- Isotopic and trace element geochemistry: mantle and crustal systems
- Metal isotopes: applications to ore formation
- Magma genesis and crustal evolution: includes trace elements of accessory minerals, isotopic fingerprints
- High-pressure experimental studies

Initial enquiries can be sent to: ccfs.admin@mq.edu.au; or to any CCFS staff.

Contact details

- **CCFS information is accessible at:**

  http://www.ccfs.mq.edu.au/

- **Contact CCFS via email at:**

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Australian Government
Australian Research Council

Glossary

AINSE	Australian Institute of Nuclear Science and Engineering
AMIRA	Australian Mineral Industry Research Association
AMMRF	Australian Microscopy and Microanalysis Research Facility
(RSES) ANU	(Research School of Earth Sciences) Australian National University
APA	Australian Postgraduate Award
ARC	Australian Research Council
BSE	Backscattered Electrons
CAS	Chinese Academy of Sciences
CAGS	Chinese Academy of Geological Sciences
CCFS	Core to Crust Fluid Systems
CET	Centre for Exploration Targeting
CMCA	Centre for Microscopy, Characterisation and Analysis (UWA)
CNRS	French National Research Foundation
CoE	Centre of Excellence
COO	Chief Operating Officer
CSIRO	Commonwealth Scientific Industrial Research Organisation
CU	Curtin University
DECRA	Discovery Early Career Researcher Award
DEST	Department of Education, Science and Training
DIATREEM	Consulting company within Access MQ Limited
DIISR	Department of Innovation, Industry, Science and Research
DP	Discovery Project
EBSD	Electron Backscatter Diffraction
ECR	Early Career Researcher
ECSTAR	Early Career Start-up Awards for Research
(D)EPS	(Department of) Earth and Planetary Sciences
EMP	Electron Microprobe
ERA	Excellence in Research for Australia
FIM	Facility for Integrated Microanalysis
FTIR	Fourier Transfer Infrared Spectroscopy
GA	Geoscience Australia (formerly AGSO)
GAC	Geological Association of Canada
GAU	Geochemical Analysis Unit (DEPS, Macquarie University)
GEMOC	Geochemical Evolution and Metallogeny of Continents
GEUS	Geological Survey of Denmark and Greenland
GIS	Geographic Information System
GLAM	Global Lithospheric Architecture Mapping
GLITTER	GEMOC Laser ICPMS Total Trace Element Reduction software
GSWA	Geological Survey of Western Australia
ICPMS	Inductively Coupled Plasma Mass Spectrometer
IPRS	International Postgraduate Research Scholarship
LAM-ICPMS	Laser Ablation Microprobe - ICPMS
LIEF	Linkage Infrastructure, Equipment and Facilities
MC-ICPMS	Multi-Collector - ICPMS
MERIWA	Minerals and Energy Research Institute of Western Australia (Pre 2014)
MRIWA	Minerals Research Institute of Western Australia (From February 2014)
(i)MQRES	(International) Macquarie University Research Excellence Scholarships
MQSIS	Macquarie University Strategic Infrastructure Scheme
MOU	Memoranda of Understanding
NASA	National Aeronautics and Space Administration
NCRIS	National Collaborative Research Infrastructure Scheme
PGE	Platinum Group Element
PIRSA	Primary Industries and Resources, South Australia
RIBG	Research Infrastructure Block Grant
SAC	Science Advisory Committee
SEM	Scanning Electron Microscope
SIRF	UWA Scholarship for International Research Fees
TIGeR	The Institute for Geoscience Research
UWA	University of Western Australia

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